Formation, self-sustainment and control of transport barriers in tokamaks

X. Garbet
CEA Cadarache

Thanks to: Y. Baranov, M. Becoulet, P. Beyer, S.Benkadda, C.Bourdelle, C. Figarella, P. Ghendrih, F. Imbeaux, E.Joffrin, X.Litaudon, D. Moreau, V.Parail, Y. Sarazin

Why Transport Barriers?

- Thermonuclear fusion:

Lawson criterion → Good confinement → Reduced turbulent transport.

- Confinement improvement is a key issue . Transport barriers provide an attractive solution.
- Need to control position and height (MHD stability).
- Relaxation oscillations appear in edge transport barriers → constraint on plasma facing components.

Strategy to control transport barriers and relaxation oscillations

- Facts:

- main instabilities are driven by the pressure gradient.

- shear flow stabilisation plays a central role, but is not the unique ingredient.

- shear of magnetic field is also a key ingredient.

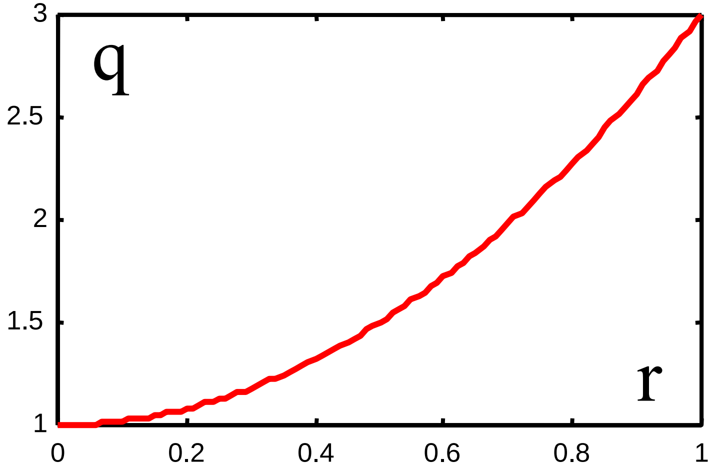
- Internal Transport Barriers : strategy is to control turbulent transport via shear flow and/or magnetic shear.
- Relaxations oscillations (and MHD): strategy is to keep the pressure away from stability limit.

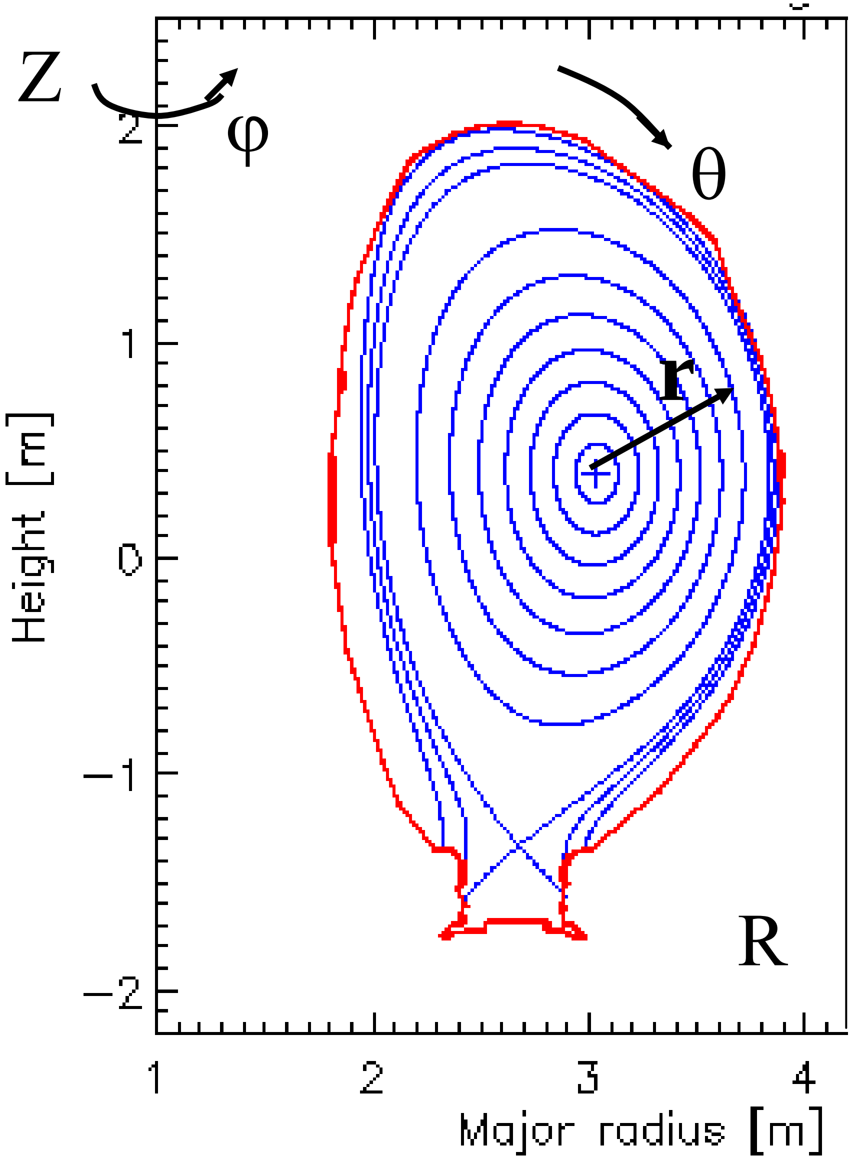
Outline

- Introduction to turbulent transport in tokamaks
- Physics of transport barriers:
  - edge transport barriers and relaxation oscillations.
  - internal transport barriers.
- Examples of control
  - internal transport barriers
  - relaxation oscillations (ELM's) in edge transport barriers.

Geometry

- Field lines generate magnetic surfaces.
- Along a field line
  q(r)=dφ/dθ
- Density and temperature are constant on magnetic surfaces.

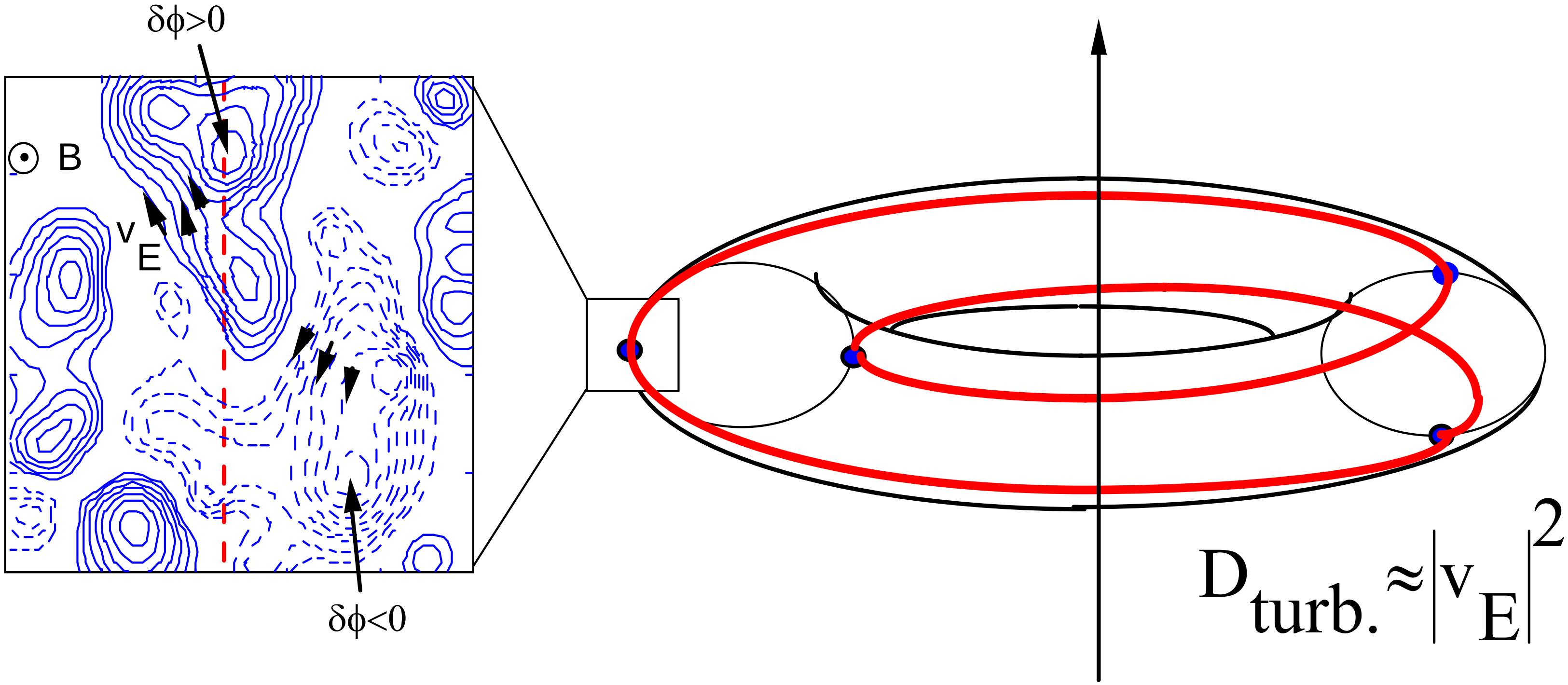




Turbulent Transport

Key ingredients:

- Fast motion along the field lines
- Perpendicular E×B Drift $v_E = \frac{B x \nabla\phi}{B^2}$



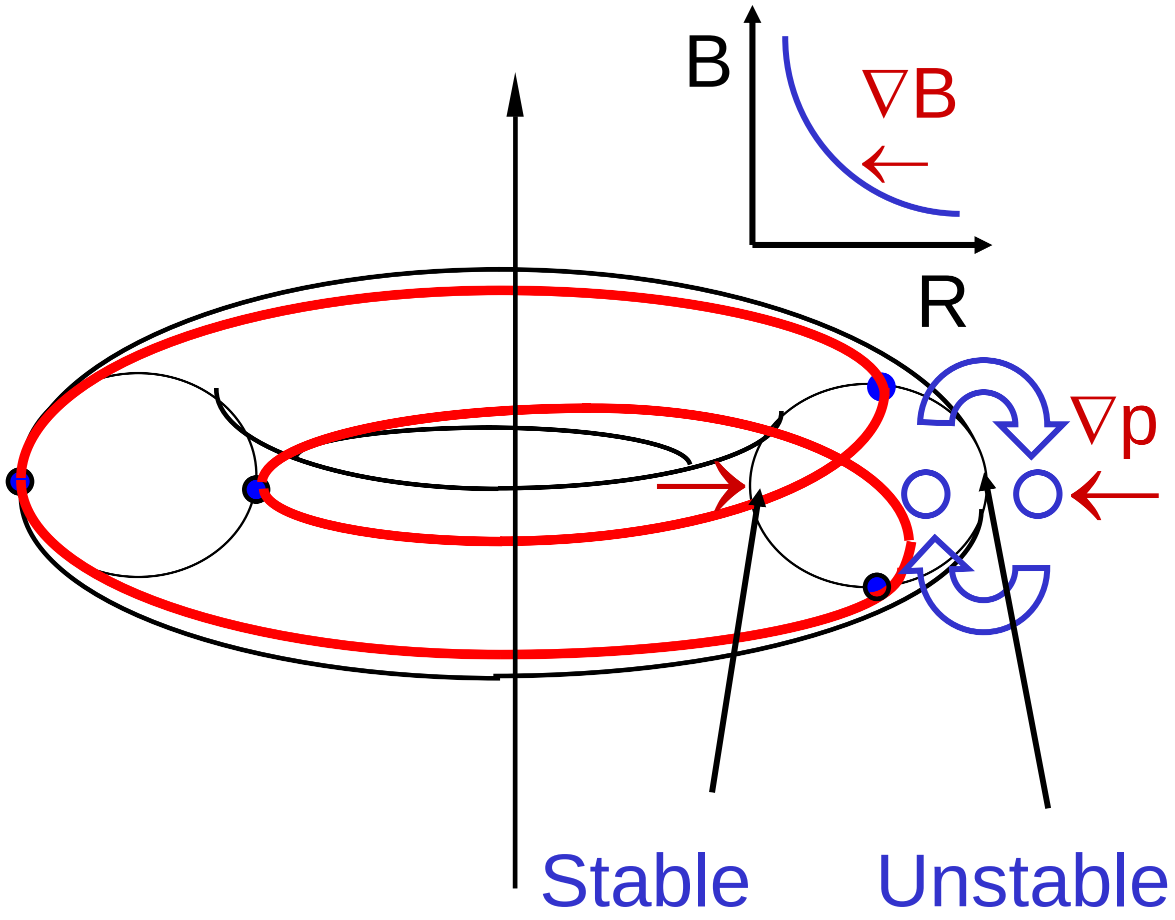
$$D_{turb.} \approx |v_E|^2 \tau_c$$

Main instabilities are interchange modes

- Exchange of two flux tubes is energetically favourable if

$(v_E \cdot \nabla B)(v_E \cdot \nabla p) > 0$

- Stable and unstable regions are connected by field lines.



Models of turbulence in tokamaks

- A key ingredient in tokamak turbulence is the interchange instability

$$d_t \nabla_\perp^2 \phi = -(\mathbf{b}.\nabla)^2 \phi + \mathbf{V_g}.\nabla p + \nu \nabla_\perp^4 \phi$$

$$d_t p = \chi_{//} (\mathbf{b}.\nabla)^2 p + \chi_\perp \nabla_\perp^2 p + S$$

$d_t=\partial_t+v_E.\nabla$; $v_E=\mathbf{B}\times\nabla\phi/B^2$

- Similarities with thermo-convection and Rayleigh-Taylor instability

$$d_t \nabla_\perp^2 \phi = \mathbf{V_g}.\nabla T + \nu \nabla_\perp^4 \phi$$

$$d_t T = \chi_\perp \nabla_\perp^2 T + S$$

- The actual plasma response is more complex.

Fluctuations of ExB drift velocity produce turbulent transport

- ExB drift

$$v_E = \frac{B \times \nabla\phi}{B^2}$$

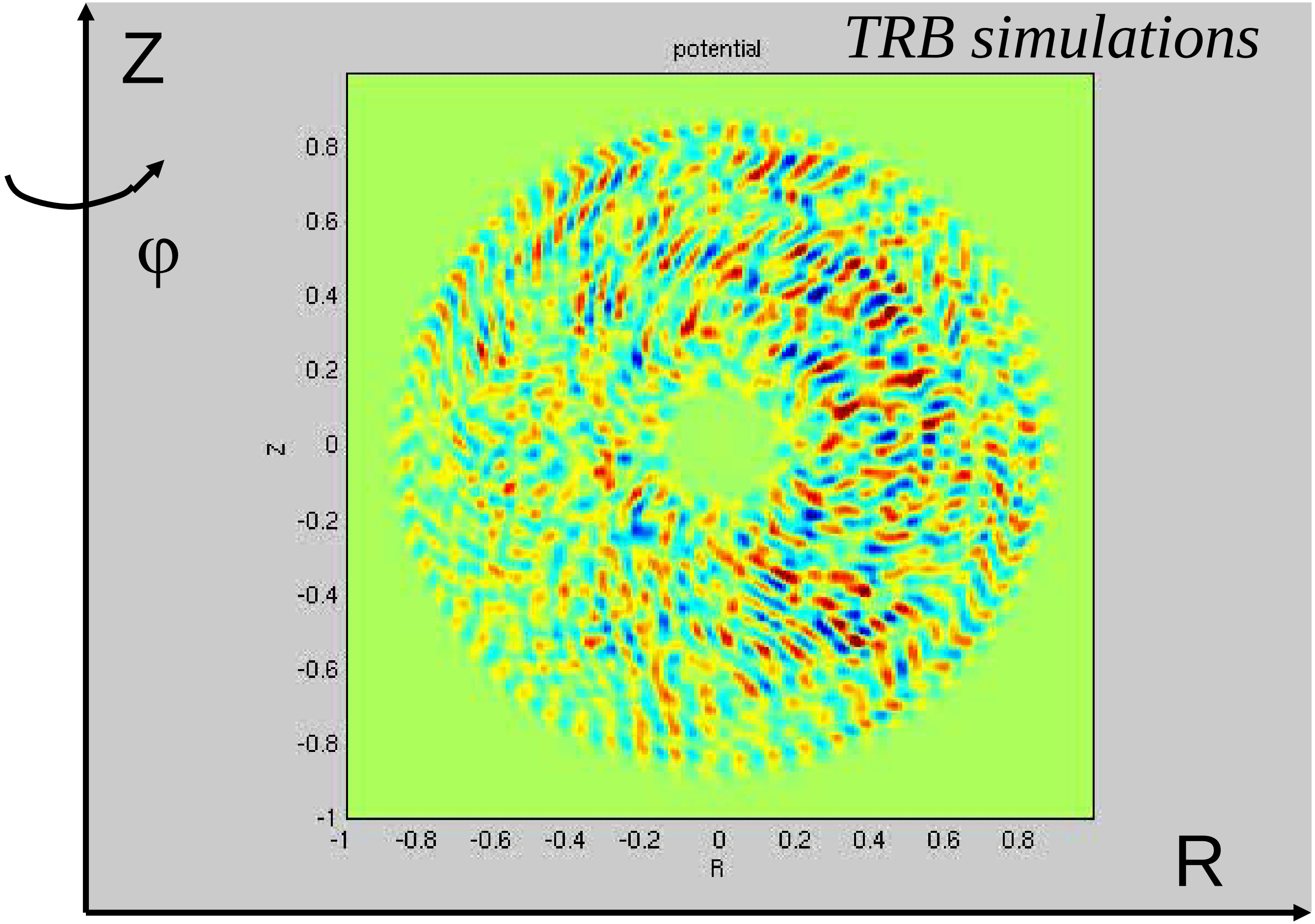
- Turbulent diffusion

$$D_{turb} \propto \left|v_E\right|^2 \tau_c$$

$$\propto L_c^2 / \tau_c$$

- Turbulent flux

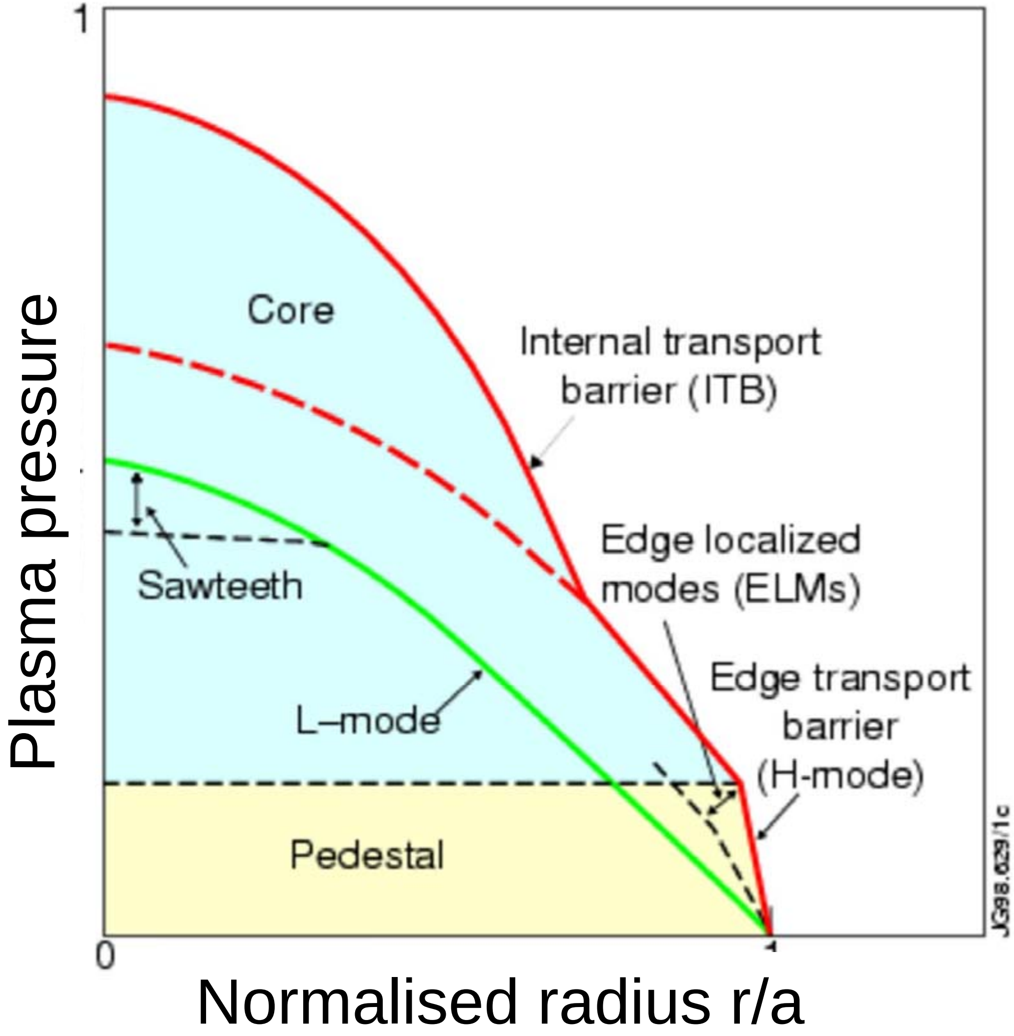
$$\phi_E = \frac{3}{2}\left\langle p v_E \right\rangle$$


TRB simulations

Contour lines of electric potential ϕ.

Several “regimes” in a tokamak plasma

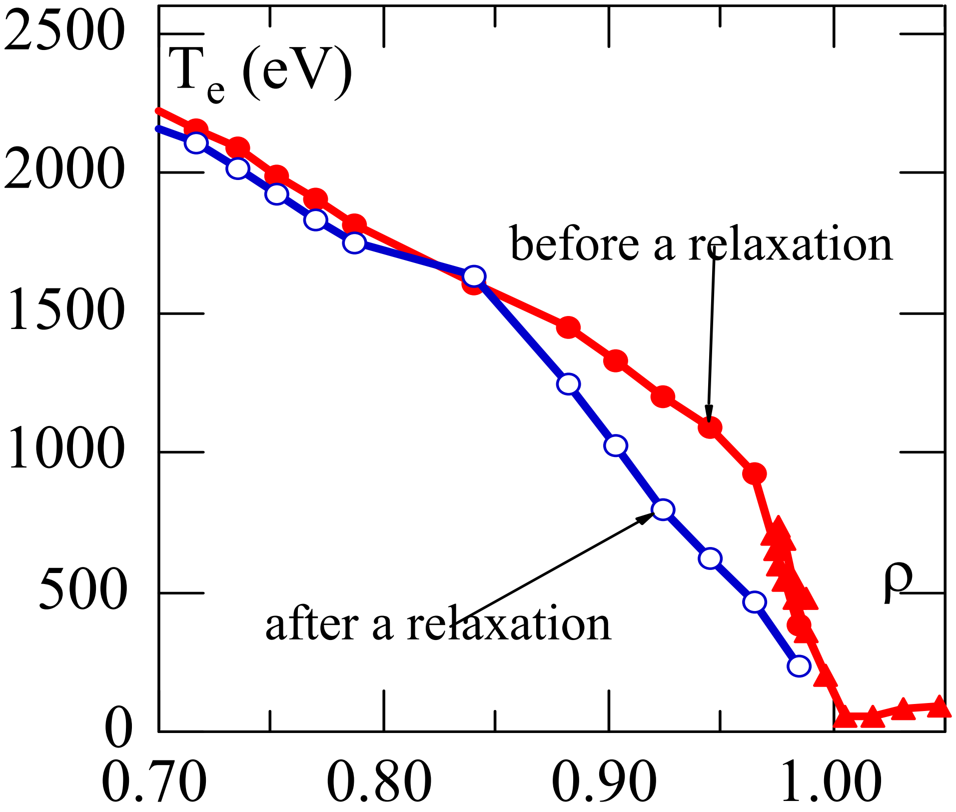
- L-mode: basic plasma, turbulence everywhere.
- H-mode: low turbulent transport in the edge, formation of a pedestal.
- Internal Transport Barrier low turbulent transport in the core, steep profiles.



Oscillations relaxations ("Edge Localised Modes") appear in H-mode plasmas

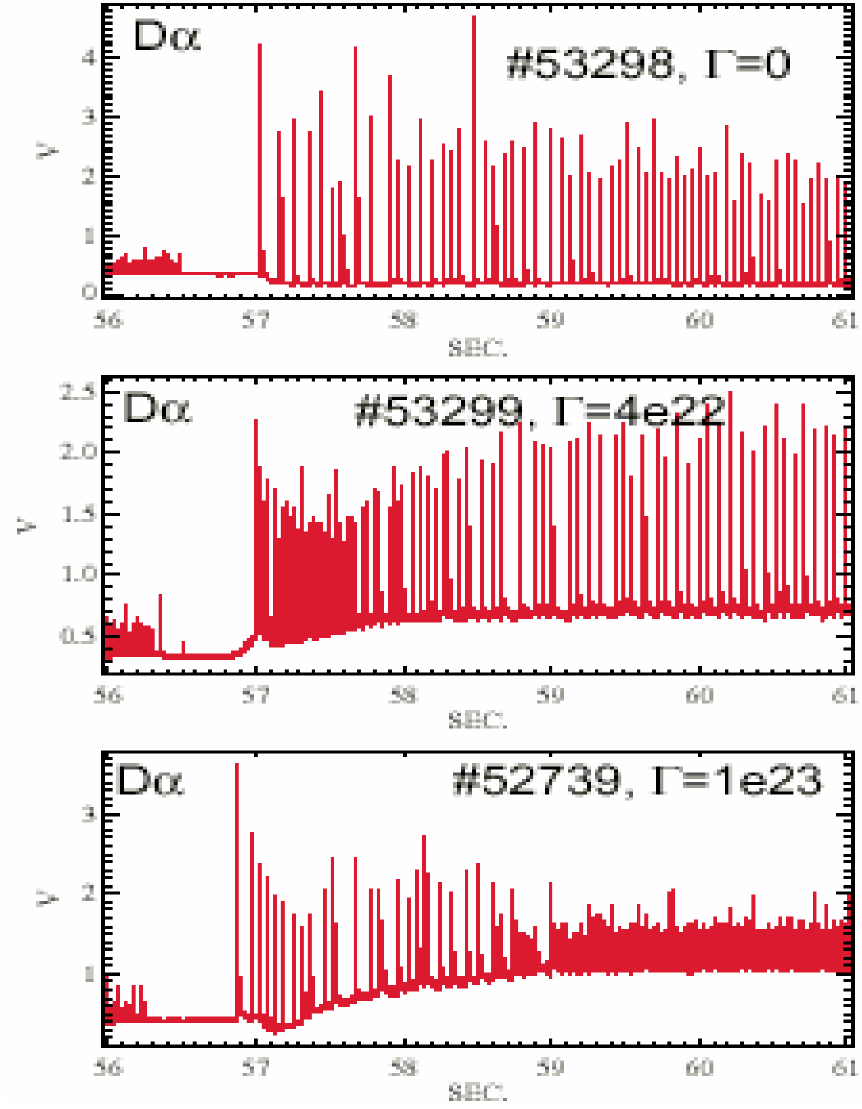
- H-mode : transport barrier in the edge due to a shear flow.
- ELM: relaxation oscillations.
- Complex temporal behaviour.

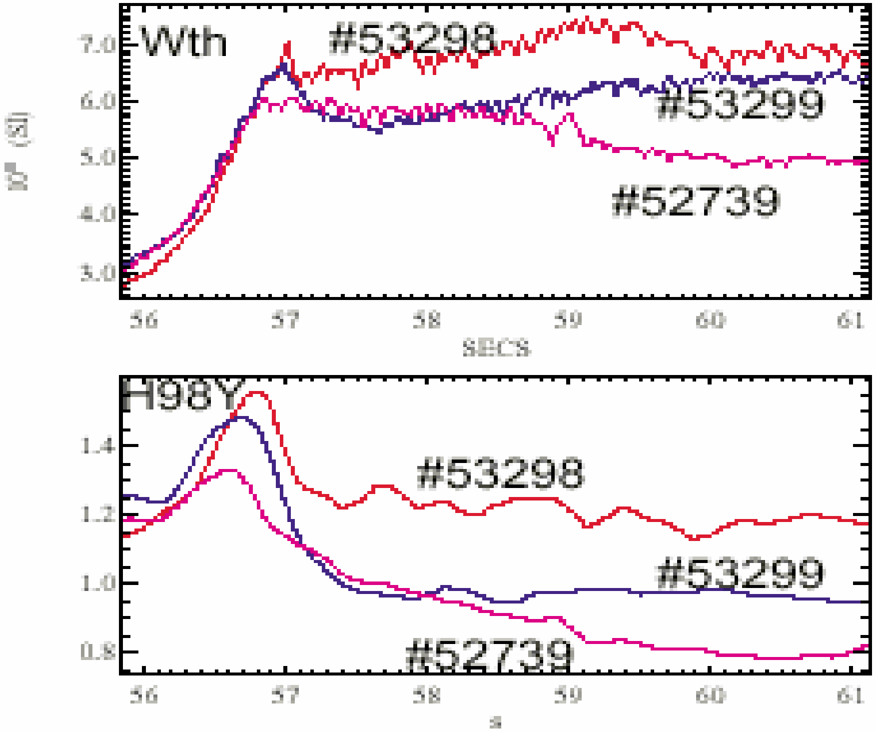
JET#58135 at t=60.118s



Monier 03

ELM's dynamics is crucial



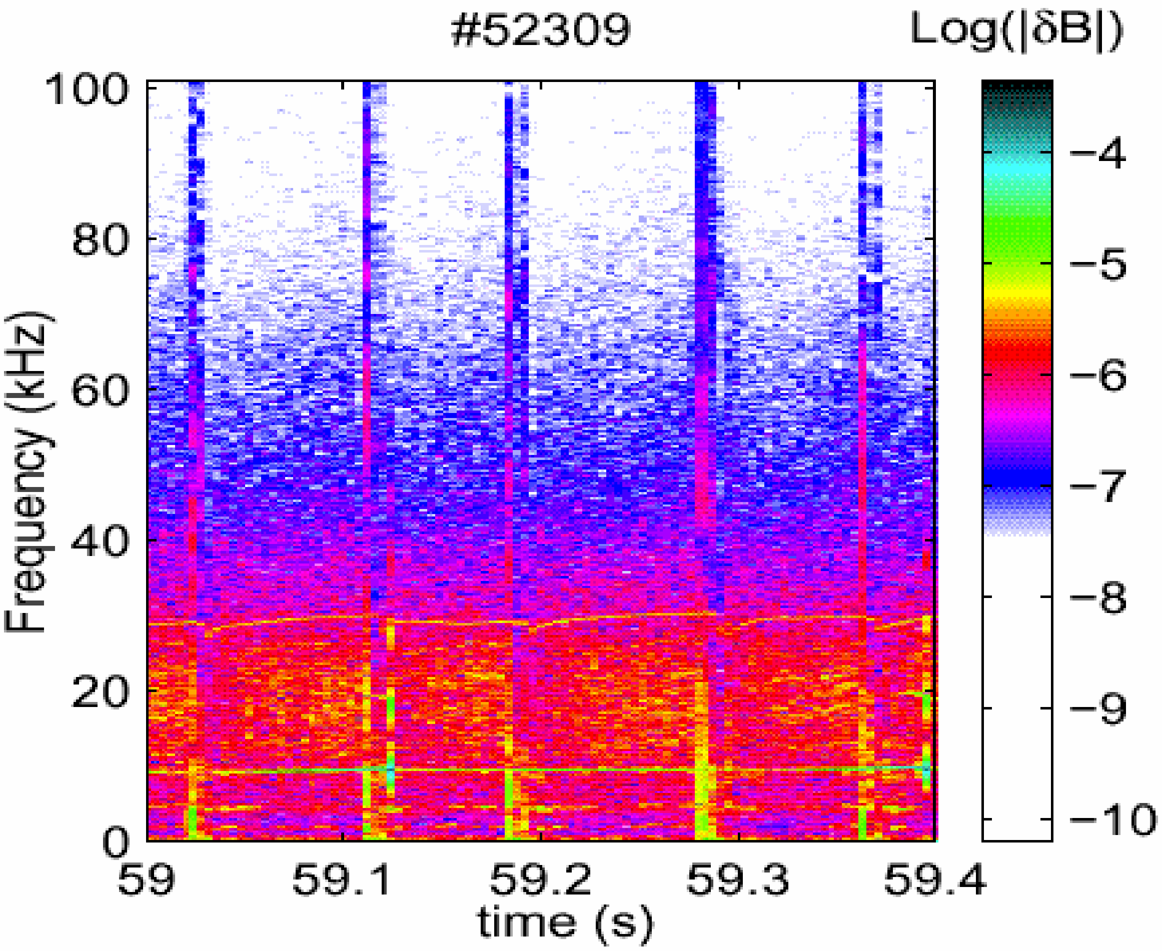


- Energy content depends on the type of ELM’s.

Parail 02

ELM's are associated to an MHD instability

- Underlying electromagnetic mode.
- Relaxation= mode growth+transport event.
- Crash time ≈100µs
- Recovery time= diffusion time.



G. Saibene 03

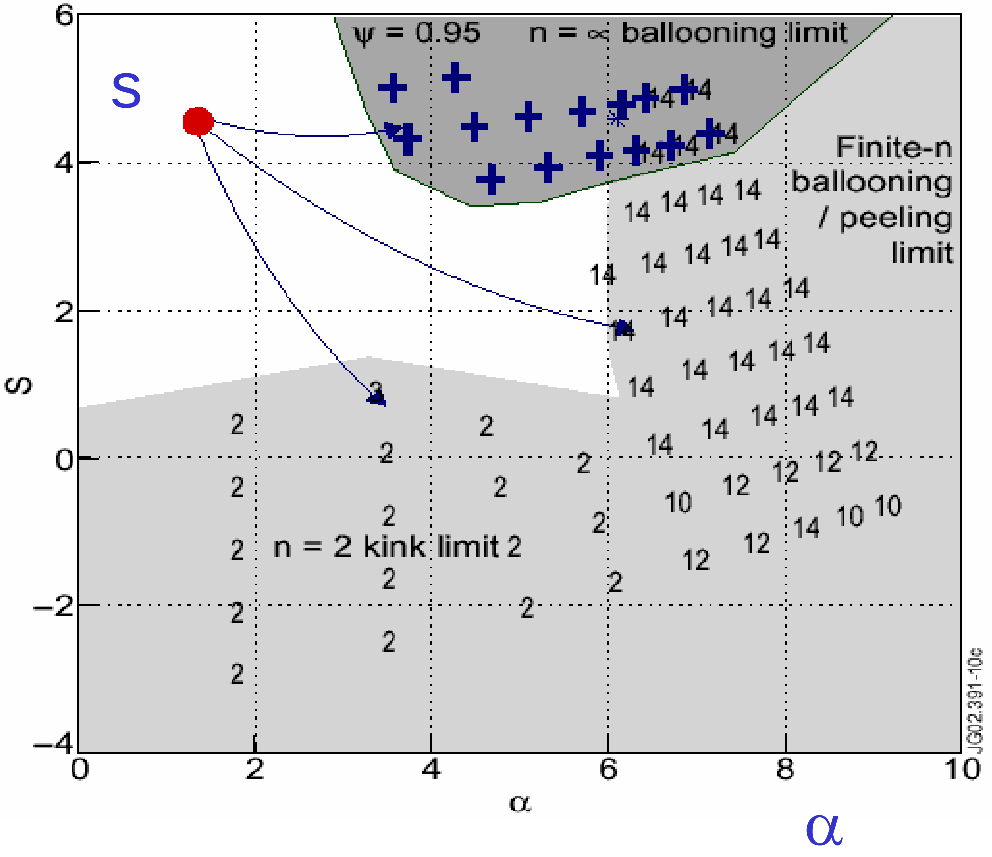
ELM's live close to an MHD limit

- Pressure (ballooning) and current (kink) driven modes.
- Stability domain pressure gradient

$$\alpha=-q^2Rd\beta/dr$$

vs magnetic shear

$$s=rdq/qdr.$$



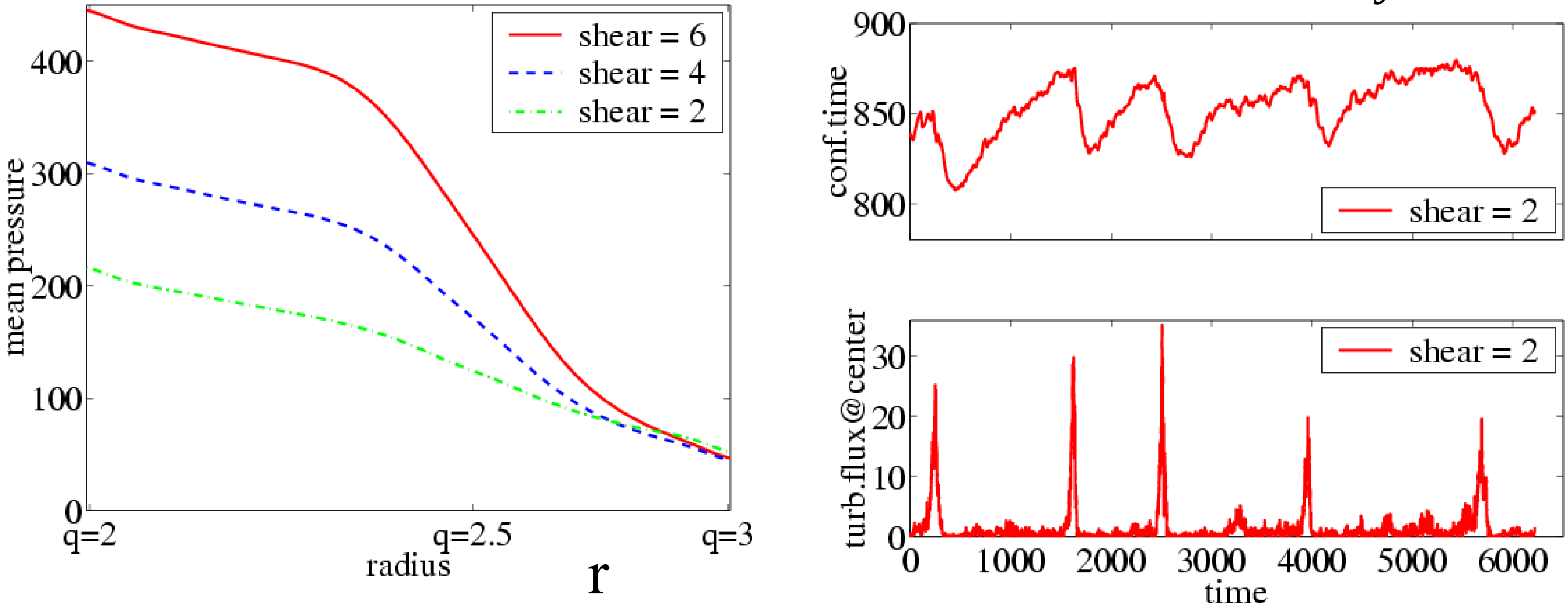
Wilson 01, Snyder 02, Parail 02, G. Huysmans 02

Lonnroth/Parail 03

Barrier Relaxations appear in simulations for a large enough velocity shear

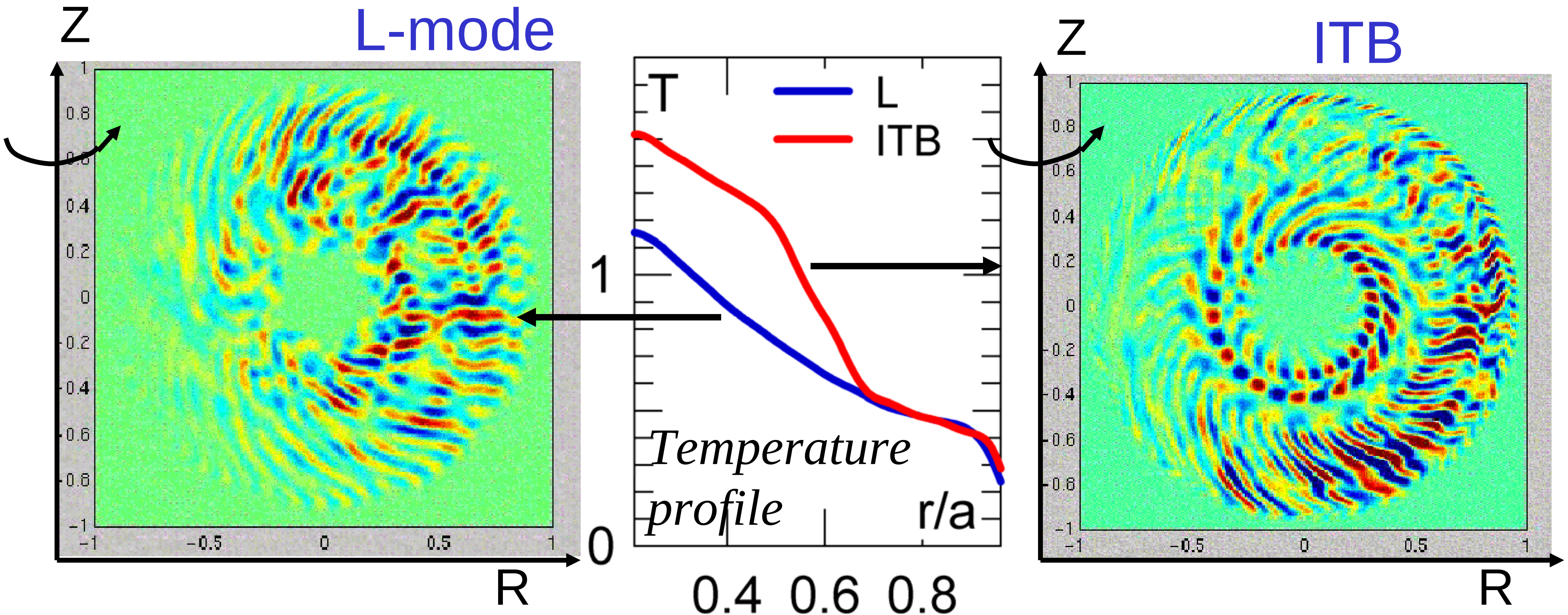
- Similarities with relaxations in edge barriers
- Link with actual ELM's is unclear yet.

P. Beyer



Physics of Transport Barriers

- Transport barriers are layers of plasma where turbulent transport is reduced.
- Requires a minimum amount of power



Contour lines of electric potential.

Contour lines of electric potential.

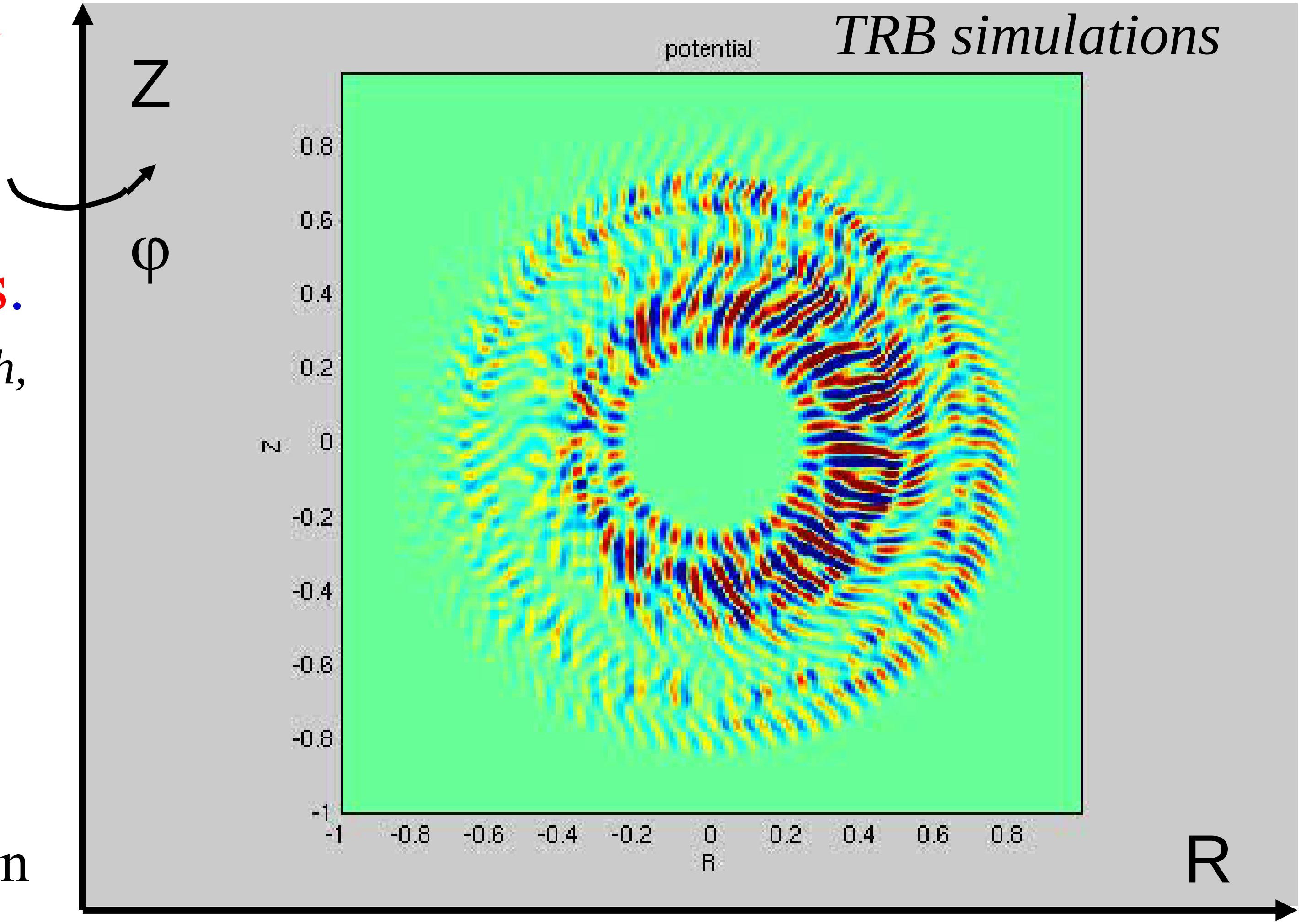
Shear flow is stabilising

- E×B velocity shear tears apart large scale vortices.

K.C. Shaing, K&S.Itoh,
K.Burrell,
P.H.Diamond,
R.Waltz, …

- Criterion for stabilisation

$$\gamma_E = \frac{dV_E}{dr} > \gamma_{lin}$$



Contour lines of electric potential.

Control of the ExB Drift in a Tokamak

- Force balance equation

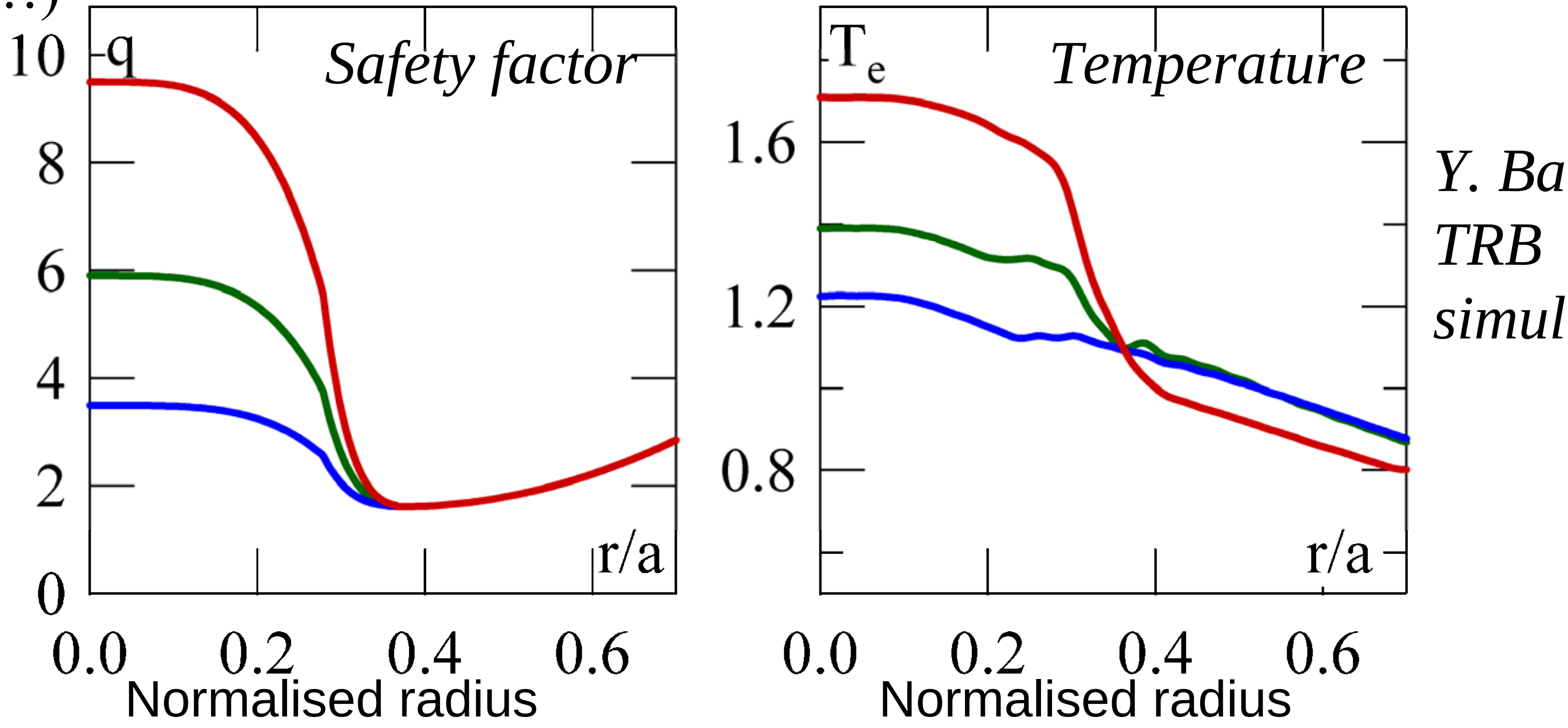
$$E_r = \underbrace{\frac{T_i dn_i}{e_i n_i dr}}_{\text{Fuelling}} + \left(1 - k_{neo}\right)\underbrace{\frac{dT_i}{e_i dr}}_{\text{Heating}} + \underbrace{V_{Ti} B_p}_{\text{Toroidal momentum}}$$

- Self-generation of mean flow

$$\partial_t V_\theta = -\nabla_r \left\langle \tilde{V}_{Er} \tilde{V}_{E\theta} \right\rangle - \nu_{neo}\left(V_\theta - V_{eq}\right)$$

Negative magnetic shear is also stabilising

- Turbulence simulations : stabilisation for s=rdq/qdr <-0.5
  (Y.Baranov, A.Bottino, R. Budny,…)
- Agrees with experiment (TORE SUPRA, TCV, FTU, JET, AUG …)



Y. Baranov, TRB simulations

Magnetic shear lowers critical shear flow at transition

- Force balance equation

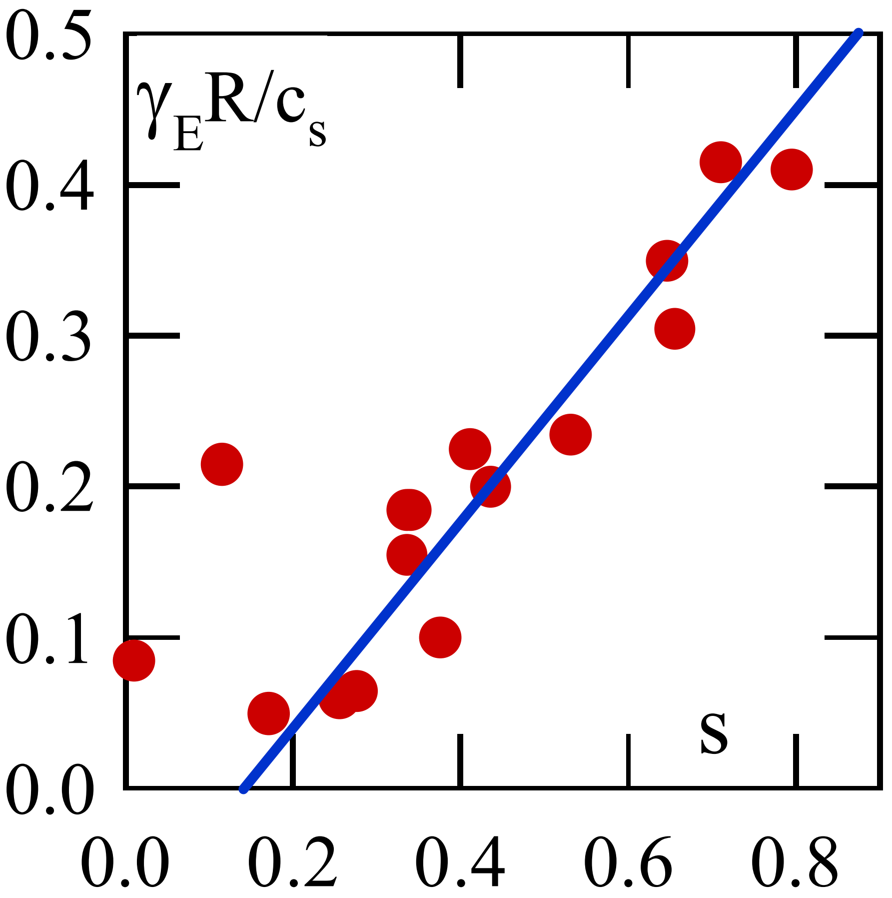
$$n_i e_i (\mathbf{E} + \mathbf{V} \times \mathbf{B}) - \nabla p_i = 0$$

→ in a reactor plasma

$$\gamma_E / \gamma_{lin} \approx \rho_T^* = \rho_s / L_T << 1$$

→ adjustement of magnetic shear s to lower γ_{lin}.

Shear flow rate vs. magnetic shear
JET- T. Tala/V. Parail

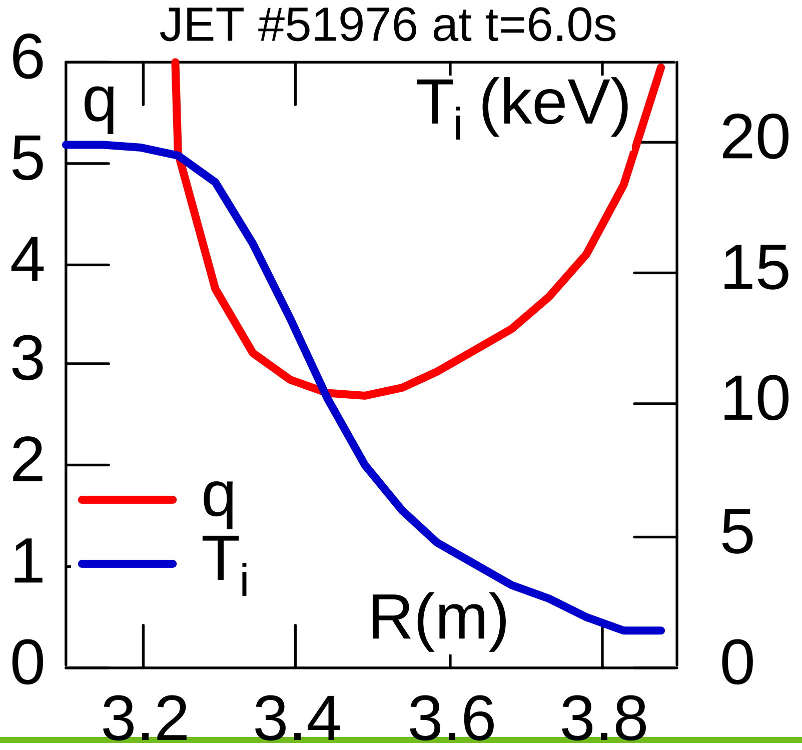


Internal Transport Barriers

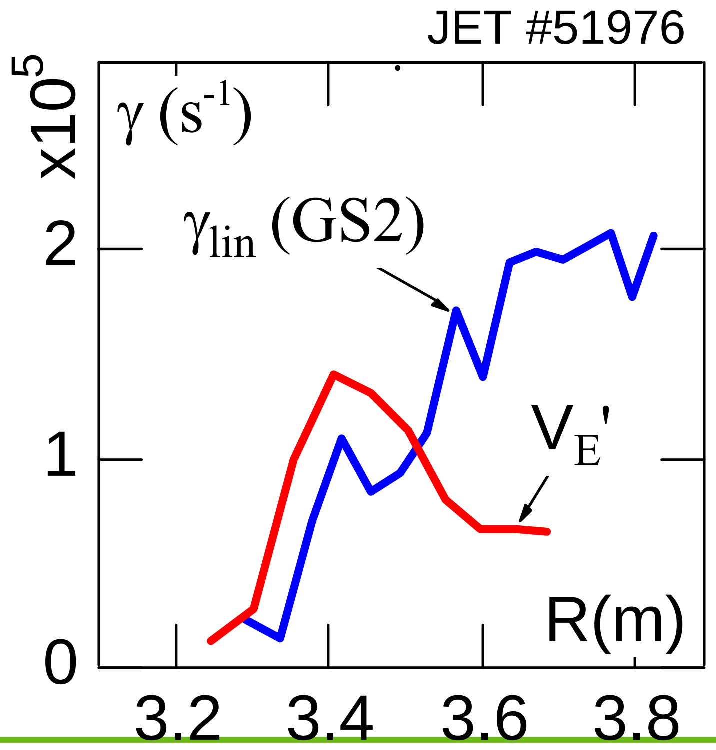
- Magnetic shear seems to be the trigger.

- Once the barrier is established, the velocity shear rate exceeds the linear growth rate.

Challis 02

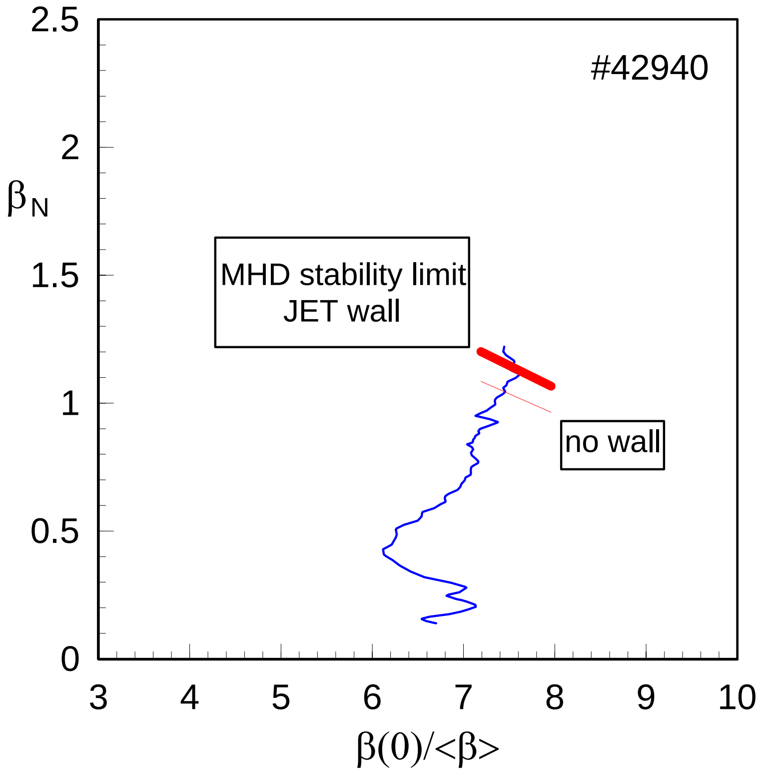


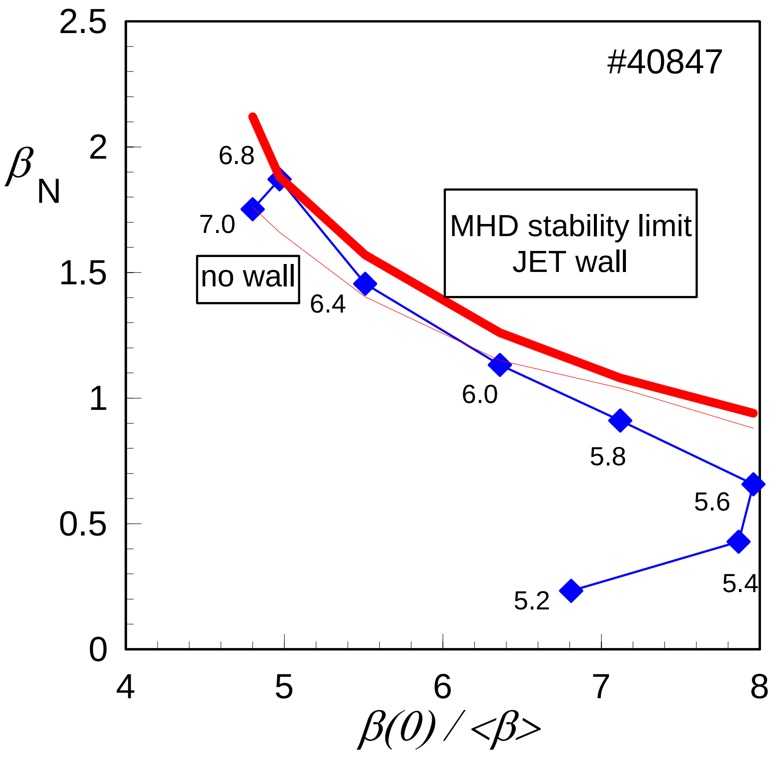
Budny 02



Control of MHD Stability

- Pressure driven MHD mode → threshold
- After optimisation.





Huysmans, JET 1999

Real-time control of internal transport barriers via velocity shear and current profile control

- Controlling γ_E and s seems an efficient way to control a transport barrier.
- Current drive provides a way to control j(r) and thus s → expensive.
- In principle γ_E can be controlled via torque, but very expensive in a reactor → shear flow rate is related to gradient

$$\gamma_E / \gamma_{lin} \approx \rho_T^* = \rho_s / L_{Te}$$

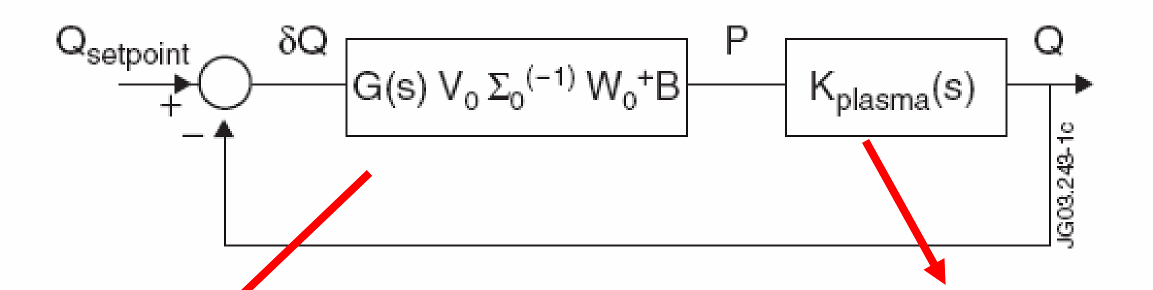
→ Control of q profile and temperature profile (ρ_T^*) with current drive heating power

Means of (global) control in a tokamak

- q profile is determined by the poloidal field → current density → controlled by current generation. Done with inductive field + waves (e.g. Lower Hybrid) or particle beams.
- Neutral Beam Injection (NBI) controls heating (mainly ions) and torque.
- Ion Cyclotron Resonant Heating (ICRH) controls heating, mainly on electrons.
- Pellet injection controls central fuelling (density)
- In a reactor :

- heating due to alpha particles (not a control parameter)
- fuelling and torque will be negligible.

Control scheme : proportional+integral feedback



Moreau 03

SVD decomposition

$$K(s)=W(s)\Sigma(s)V^{+}(s)$$

Applied power levels at time=*t*

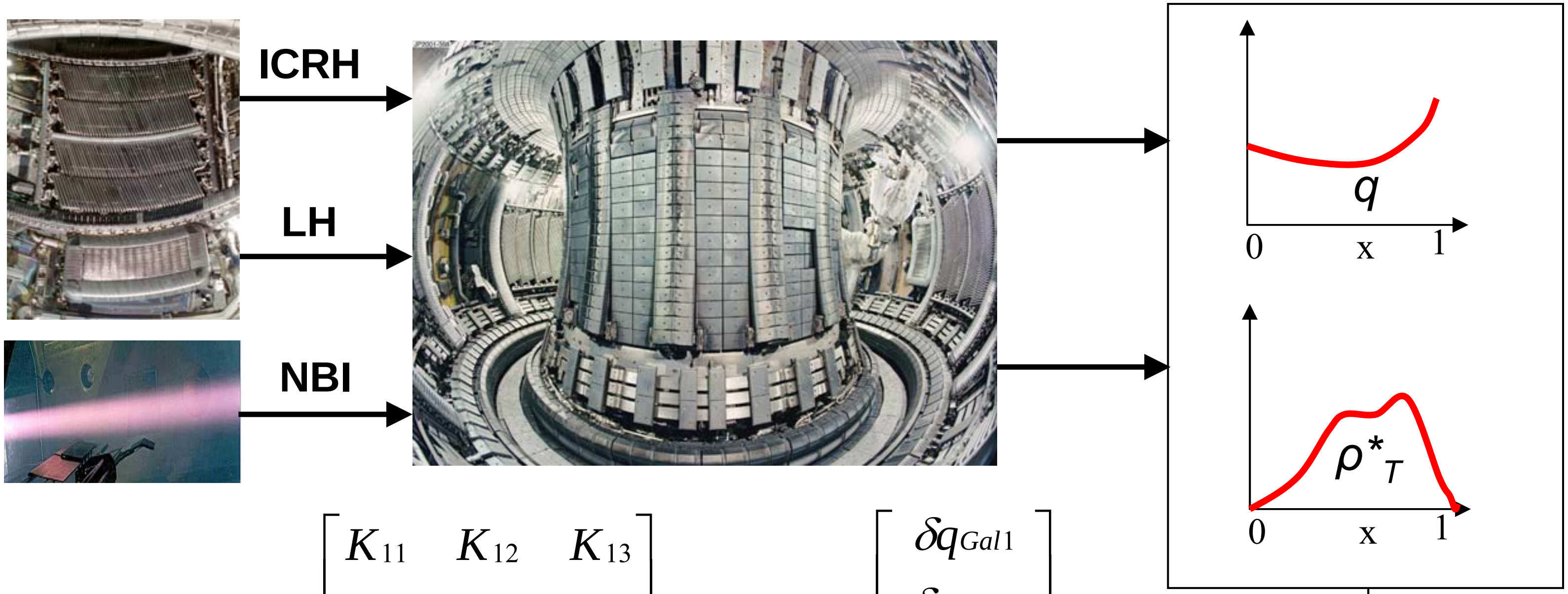
Power levels when control starts

The feedback control matrix

Difference between the target and actual *q* and ρ_t^*

$$\begin{pmatrix} P_{LH}(t)\\ P_{NB}(t)\\ P_{RF}(t)\end{pmatrix} = \begin{pmatrix} P_{LH}(t_0)\\ P_{NB}(t_0)\\ P_{RF}(t_0)\end{pmatrix} + g_c\left(1+\frac{1}{\tau_c}\int_{t_0}^{t} dt\right)\times\begin{pmatrix} q_{1LH} & q_{2LH}\cdots & \rho^{*}_{t\,LH}\cdots\\ q_{1NB} & q_{2NB}\cdots & \rho^{*}_{t\,NB}\cdots\\ q_{1RF} & q_{2RF}\cdots & \rho^{*}_{t\,RF}\cdots\end{pmatrix}\begin{pmatrix} q_{1,setpoint}-q_1(t)\\ q_{2,setpoint}-q_2(t)\\ \cdots\cdot\\ \rho^{*}_{t,setpoint}-\rho^{*}_{t}(t)\\ \cdots\cdot\cdot\end{pmatrix}$$

Algorithm for controlling current and pressure profiles

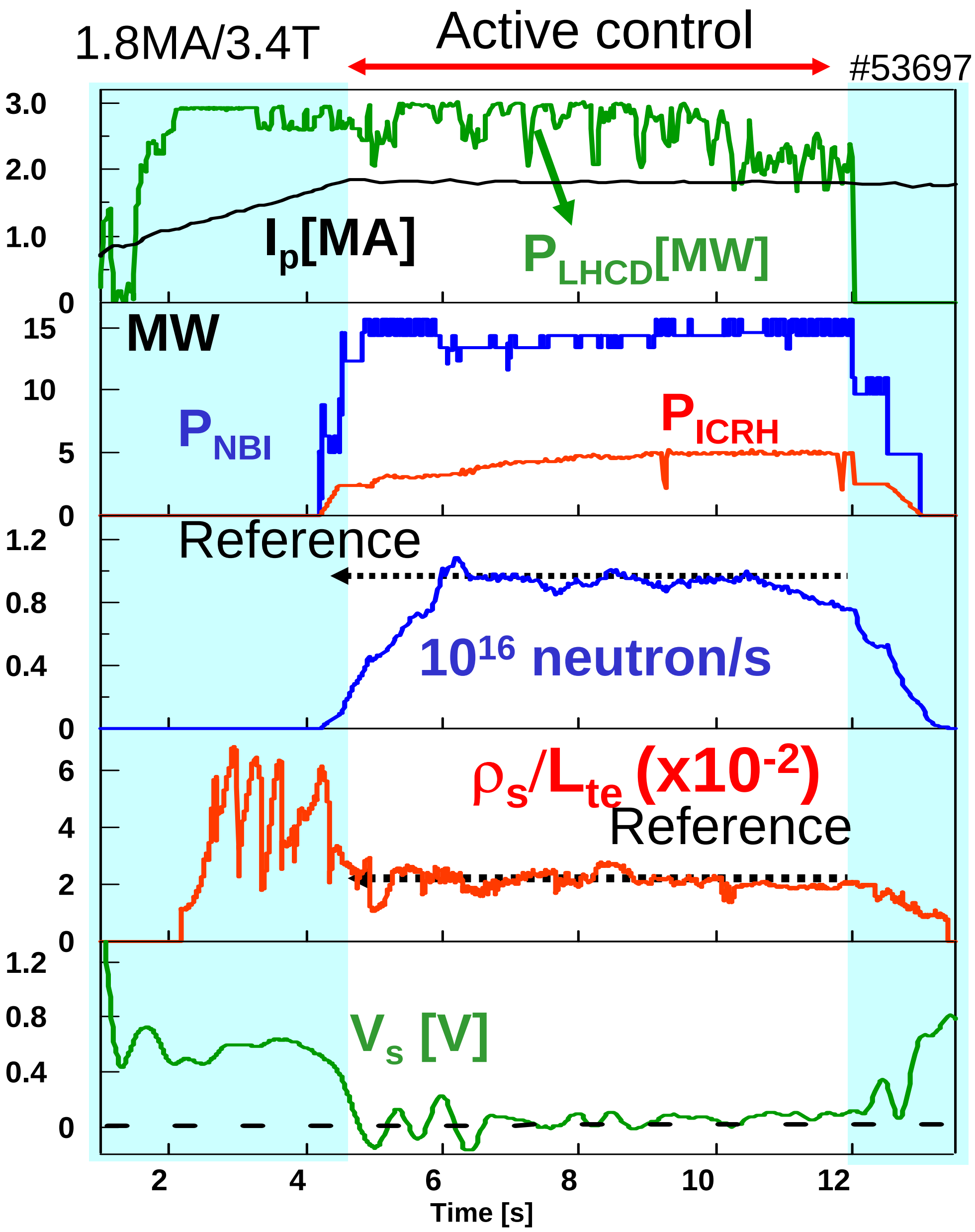


3 modulations around a reference steady-state :

$$\begin{bmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \\ K_{41} & K_{42} & K_{43} \\ K_{51} & K_{52} & K_{53} \\ K_{61} & K_{62} & K_{63} \\ K_{71} & K_{72} & K_{73} \\ K_{81} & K_{82} & K_{83} \end{bmatrix} \cdot \begin{bmatrix} \delta P_{ICRH} \\ \delta P_{LH} \\ \delta P_{NBI} \end{bmatrix} = \begin{bmatrix} \delta q_{Gal1} \\ \delta q_{Gal2} \\ \delta q_{Gal3} \\ \delta q_{Gal4} \\ \delta q_{Gal5} \\ \delta \rho^*_{T\ Gal1} \\ \delta \rho^*_{T\ Gal2} \\ \delta \rho^*_{T\ Gal3} \end{bmatrix}$$

Galerkin's algorithm

Moreau 03



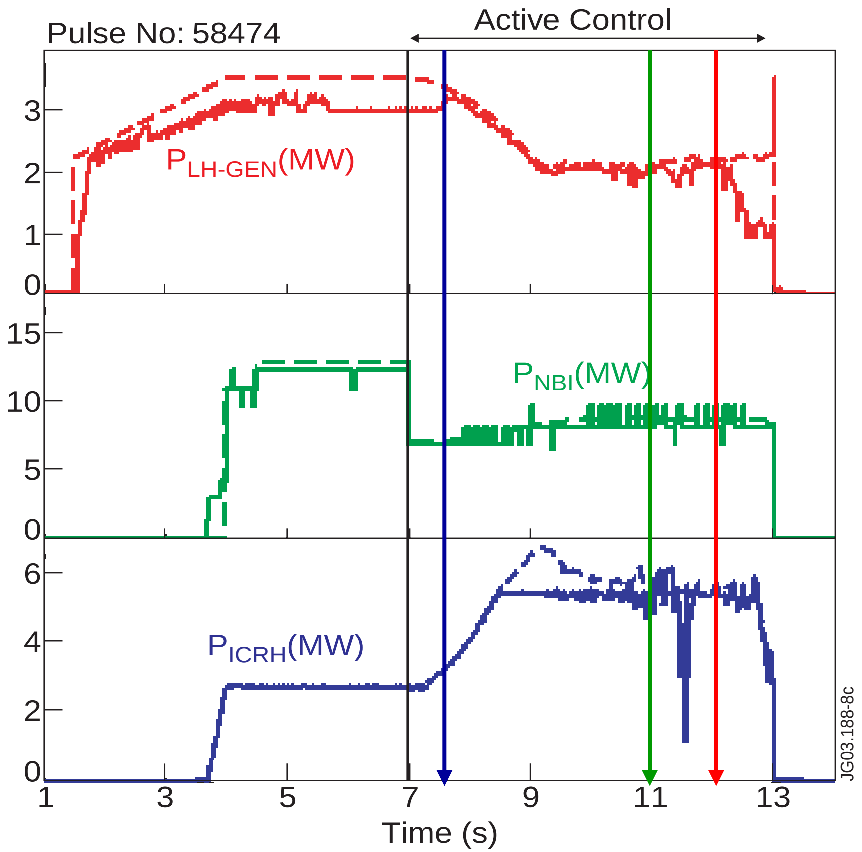
An example of control

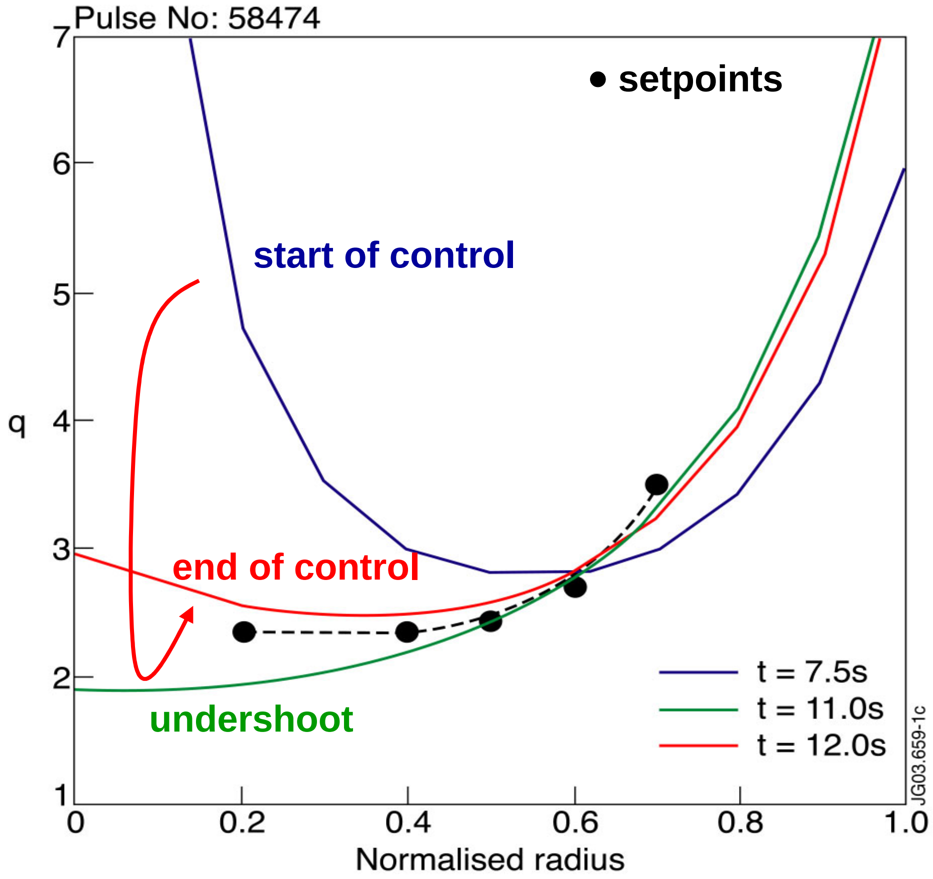
- ITB is controlled during 7.5s with ≈100% of non-inductive current.
- Neutral beam injection controlled by neutron emission
- Radio-frequency heating controlled by ρ_s/L_{Te} at the barrier location
- Plasmas are more stable with RT control

Mazon 02

First q-profile control in the high power phase

1.8MA / 3.0T $H \times \beta_N \sim 2$



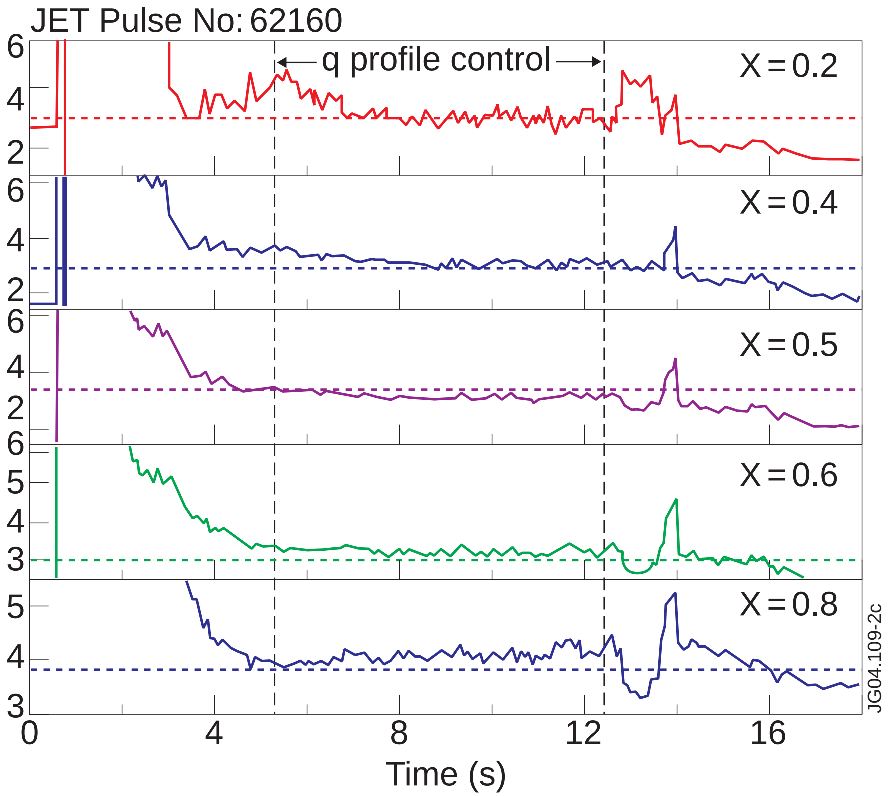


"Model Based SVD control" deduced from open loop experiments

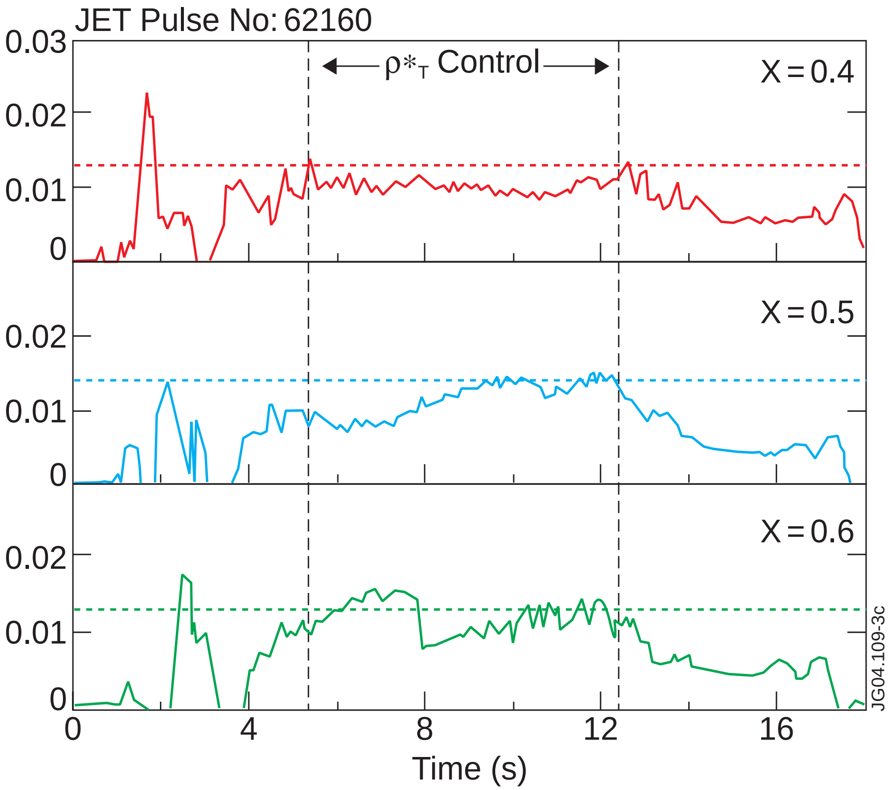
Mazon 04

First simultaneous control of q-profile and ITB strength

q profile control



ρ^*_{Te} control



- **3T/1.7MA H_{89}x β_N ~ 3.4**

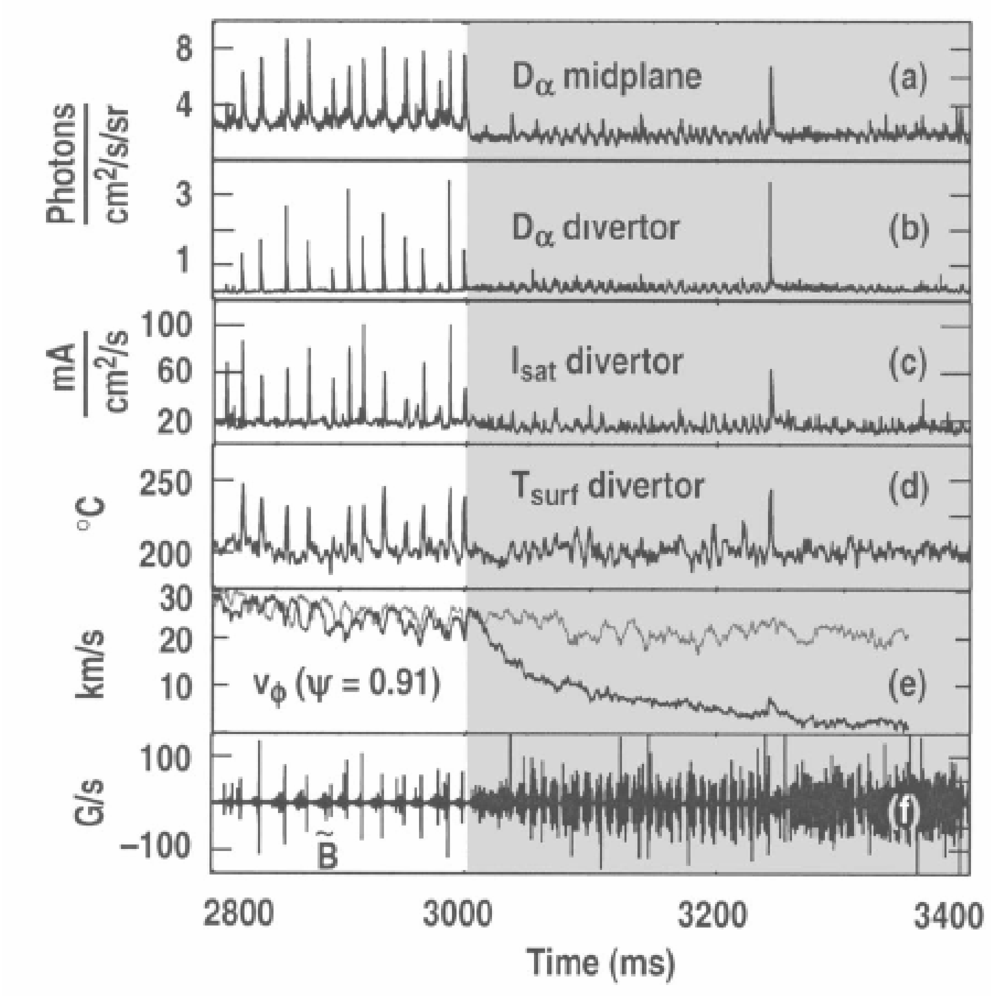
- Control performed either with a monotonic or a non-monotonic q-profile

Control of oscillation relaxations with external coils.

T.E. Evans

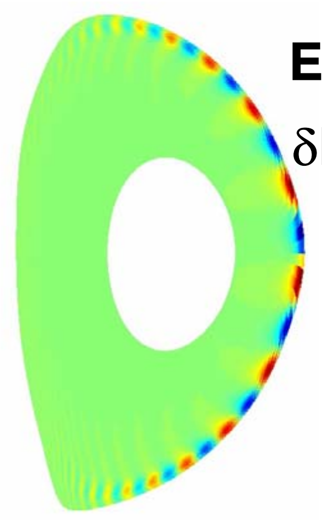
DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

- Use of magnetic coils to ergodise field lines at the edge.
- Aim is to decrease the local pressure gradient to avoid crossing the stability threshold.



Control of oscillation relaxations with external coils (cont.)

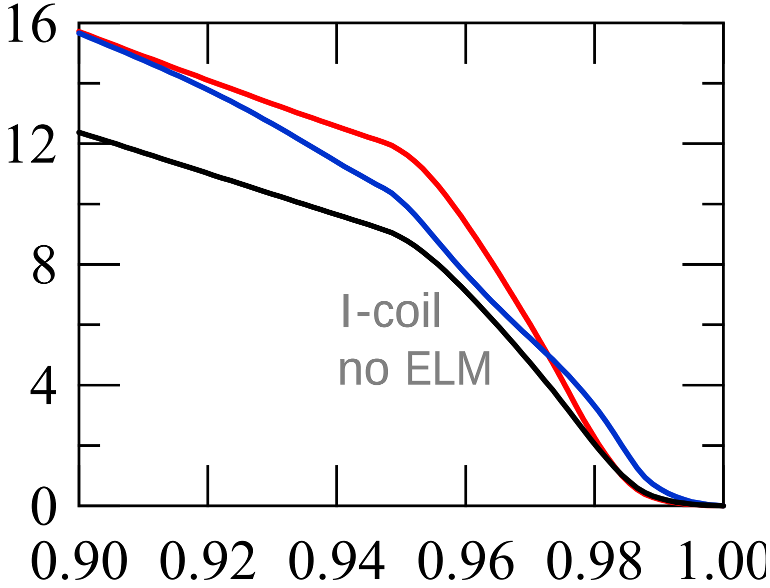
M. Becoulet 2004

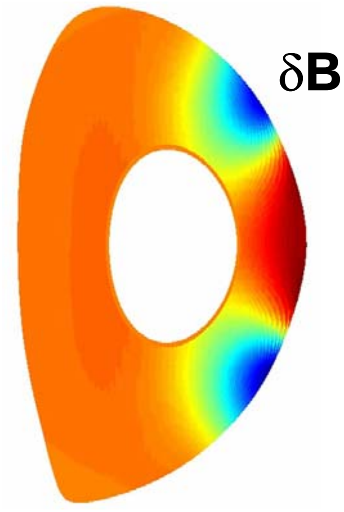


ELM δB_r (n=-10)

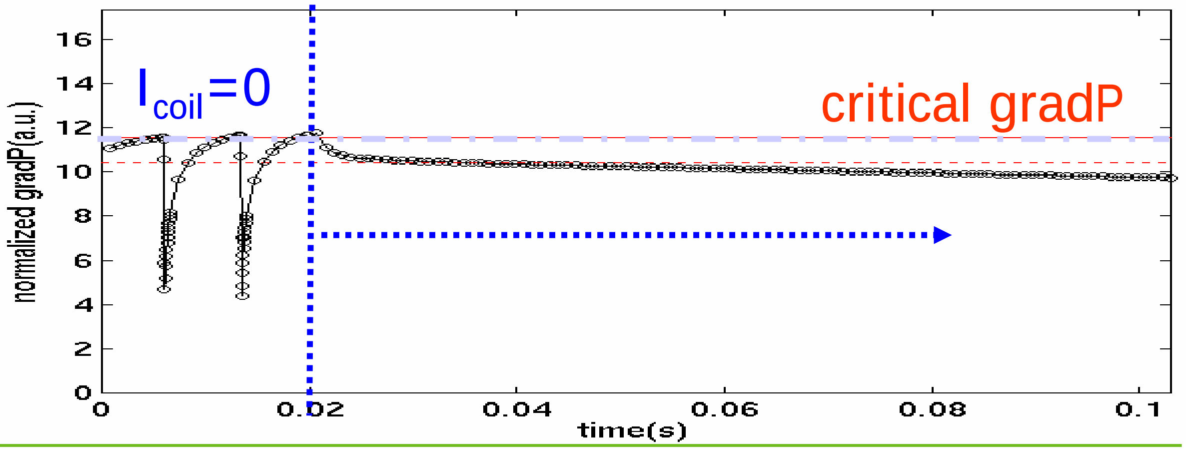
$\delta B_r \sim 10^{-2}$

DIII-D:# 115467
1.6T/1.13MA
q_{95}=3.8
I-coil=4kA





$\delta B_r \sim 10^{-4}$



Conclusions

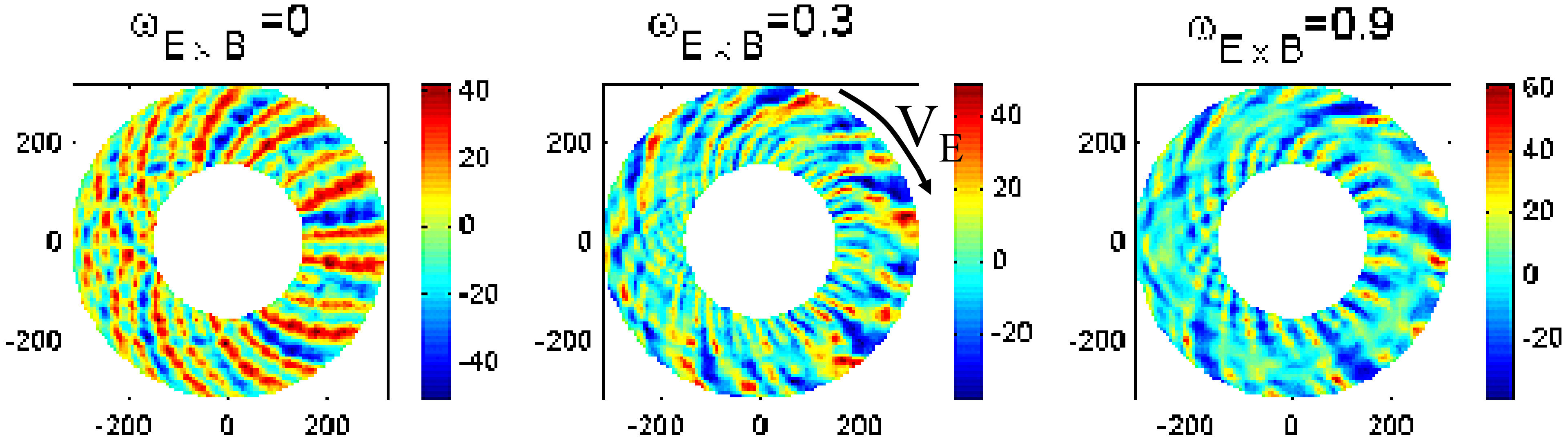
- Control of confinement and stability seems feasible with macroscopic quantities such as magnetic shear, velocity shear and density gradient.
- Magnetic shear requires current drive: expensive but feasible.
- Control of rotation seems much more difficult in a reactor: torque due to beams is small → means to generate rotation with RF waves.
- On a longer term, more sophisticated control techniques will be necessary.

Effect of a Shear Flow

- Shear flow rate $V_E' = \frac{dV_E}{dr}$
- Approximate criterion for stabilisation

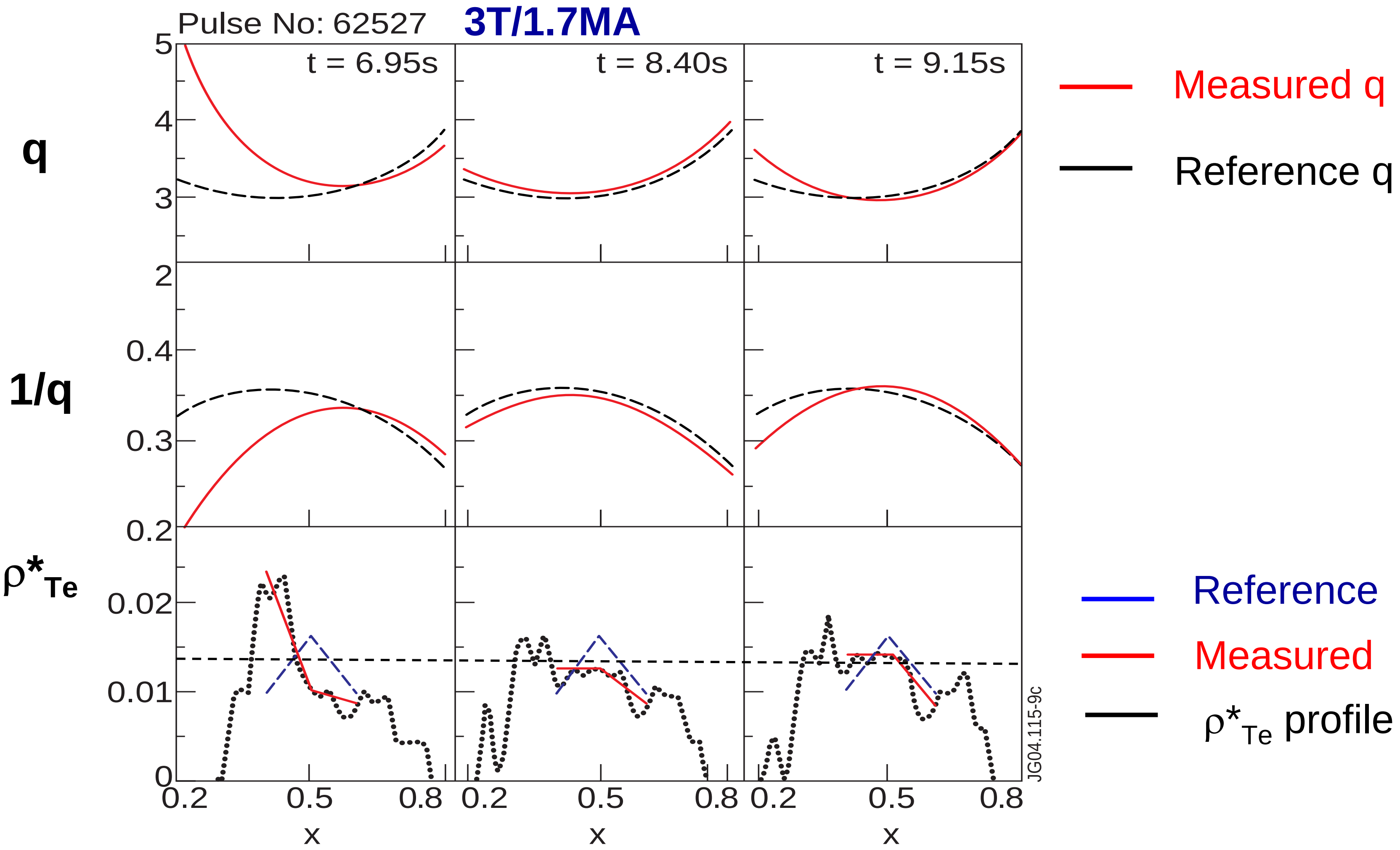
$$\left(Dk_\theta^2 V_E'^{\,2}\right)^{1/3} > \tau_c^{-1} \qquad\qquad V_E' > \gamma_{lin}$$

Biglari-Diamond-Terry 90 Waltz 94



Figarella 03

Simultaneous control of q-profile and ITB location



Effect of a Shear Flow on Transport

- Acts on amplitude and cross-phase of fluctuations

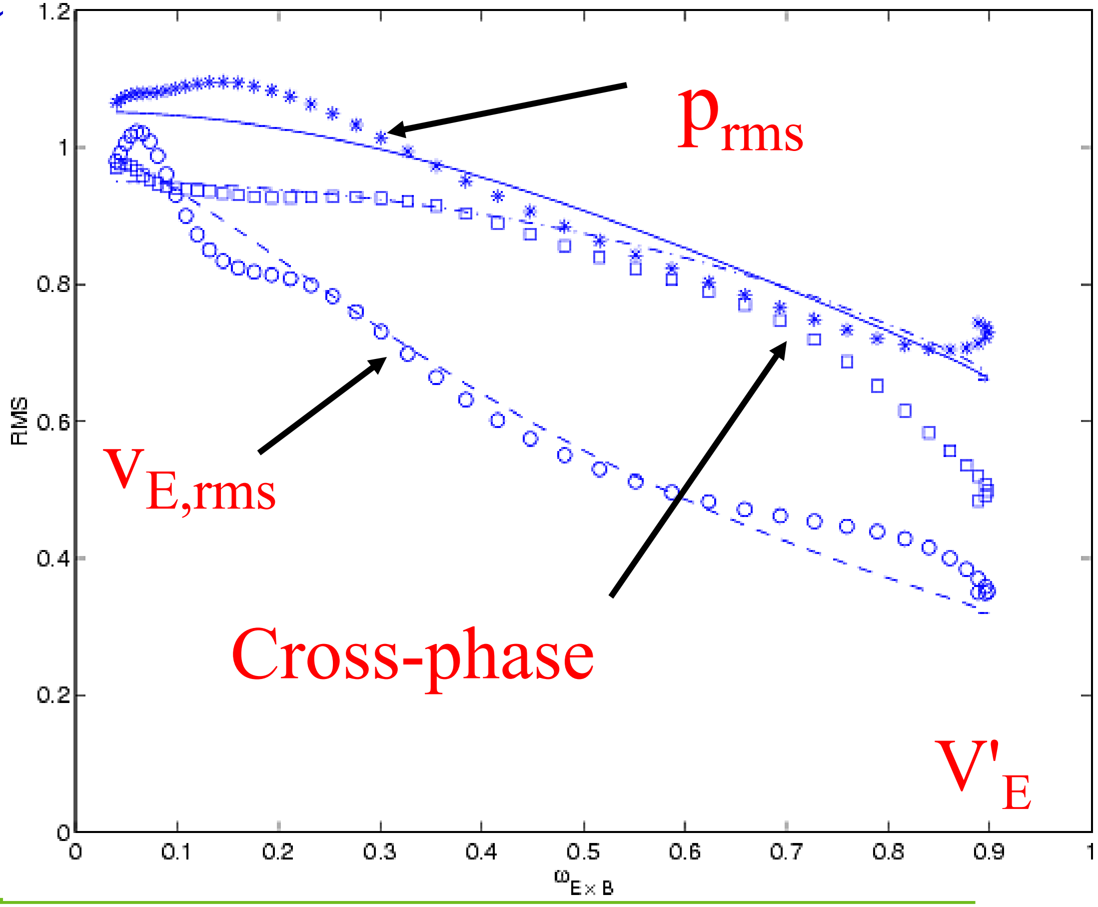
$$\Gamma=3/2<p\mathbf{v}_E>$$

- Leads to a transport barrier

$$\Gamma=-D_{turb}\nabla n_{eq}$$

$$D_{turb}\downarrow \ \rightarrow \ \nabla n_{eq}\uparrow$$

Figarella 03



p_{rms}

$v_{E,rms}$

Cross-phase

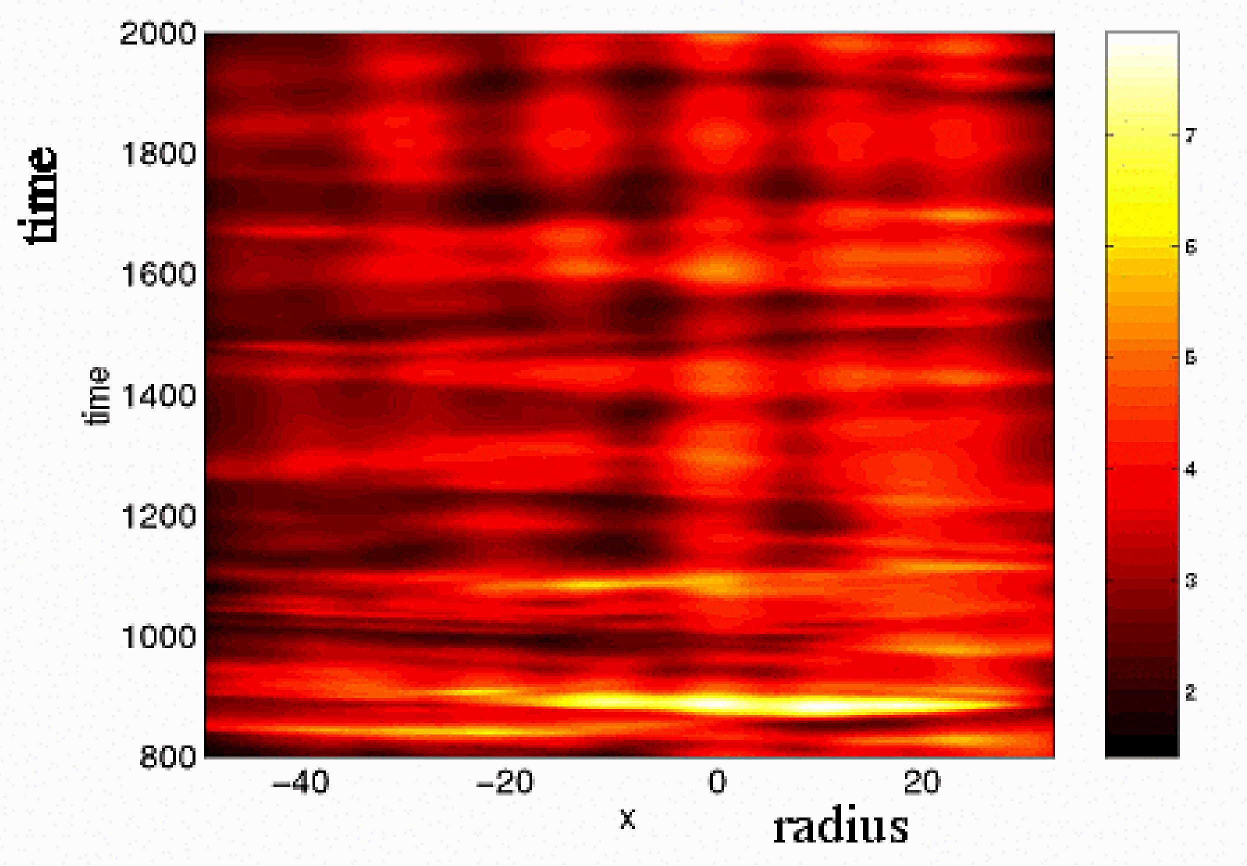
V'_E

The interaction between structures and transport barriers

- Structures have been found to play in important role in tokamak turbulence.
- Zonal Flows are fluctuations of the poloidal velocity and play a stabilizing role.
- Streamers are convective cells elongated in the radial direction : enhance the turbulent transport.
- Avalanches are large scale transport events; Connected to streamers.
- Interplay with transport barriers?

Avalanches are Large Scale Transport Events

- Evidence : maps of turbulent flux versu time and radius. Same for pressure.
- Observed in many simuations Carreras 96, Sarazin and Gendri 98, Garbet and Waltz 98, Beyer et al. 99, Candy and Waltz 02, …

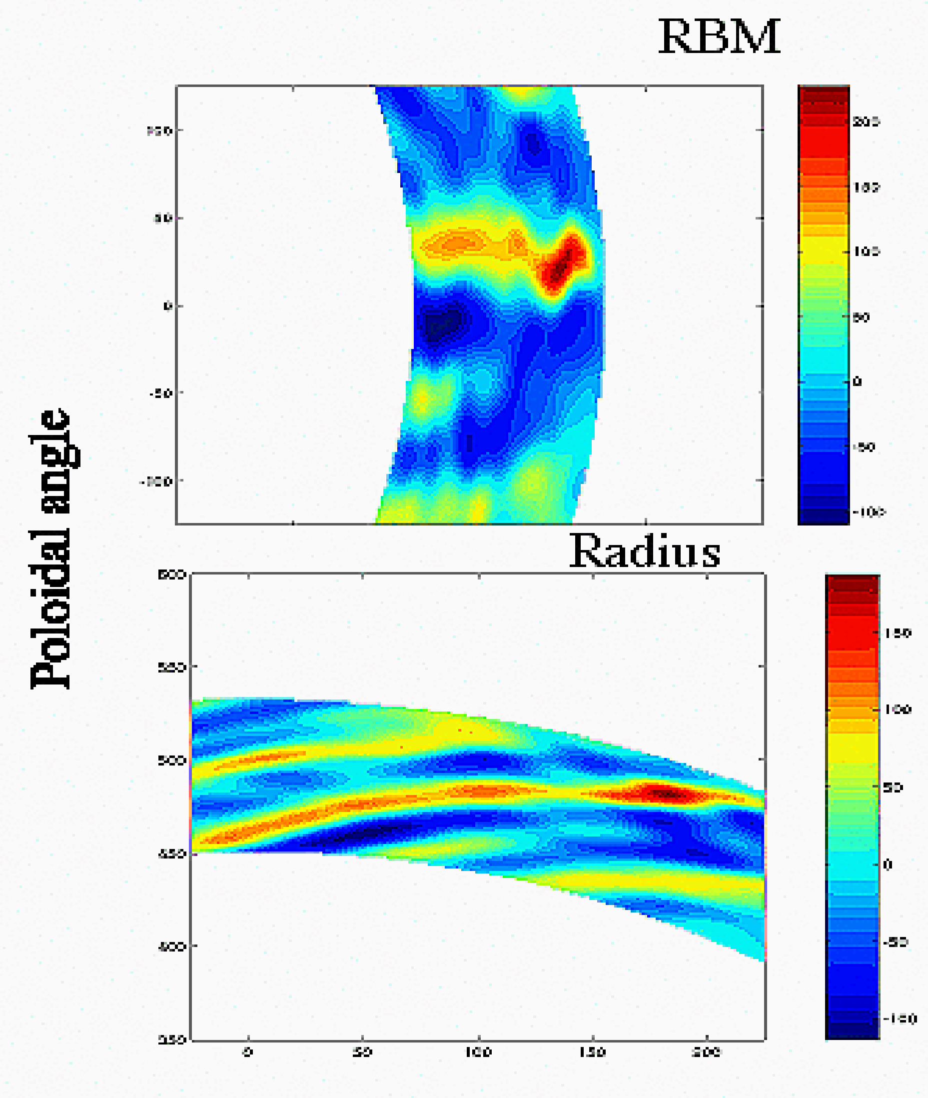


Beyer et al 99

3D Structure of an avalanche

- Maps of the flux in poloidal planes.
- Elongated structures in the radial direction: **streamers**.

  Drake 88, Diamond 99, Jenko 00
- Elongated vortices along the equilibrium magnetic field.



Beyer et al 00

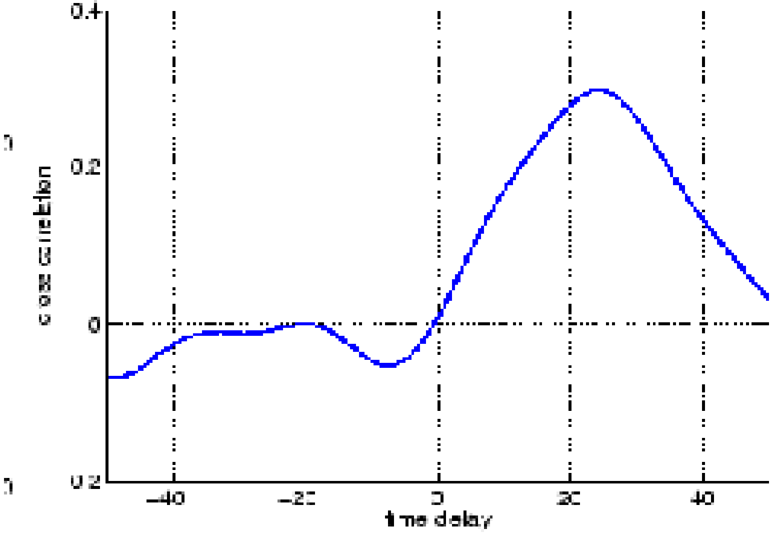
Interaction with Zonal Flows

- Streamers in low k turbulence seem to be non linear structures:

  - several toroidal wave numbers.

  - growth time scale is not linear.

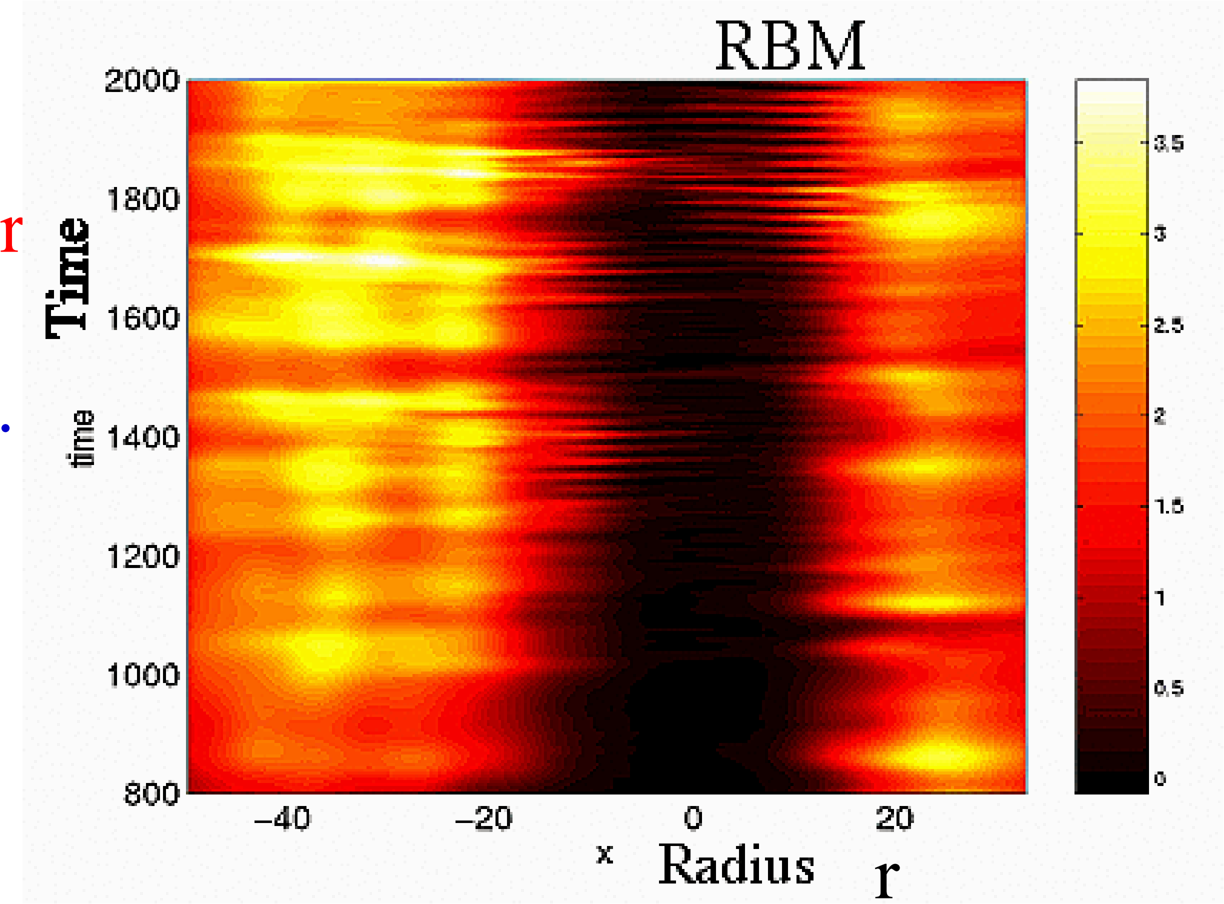
- Mechanism for the onset of a streamer still unclear.
- Interplay with Zonal Flows.



Cross correlation between turbulent flux and ExB shear flow: time delay.

Avalanches hardly cross a transport barrier

- Suggests an effect of the velocity shear on the propagation of a transport event.
- Some large events cross the barrier.



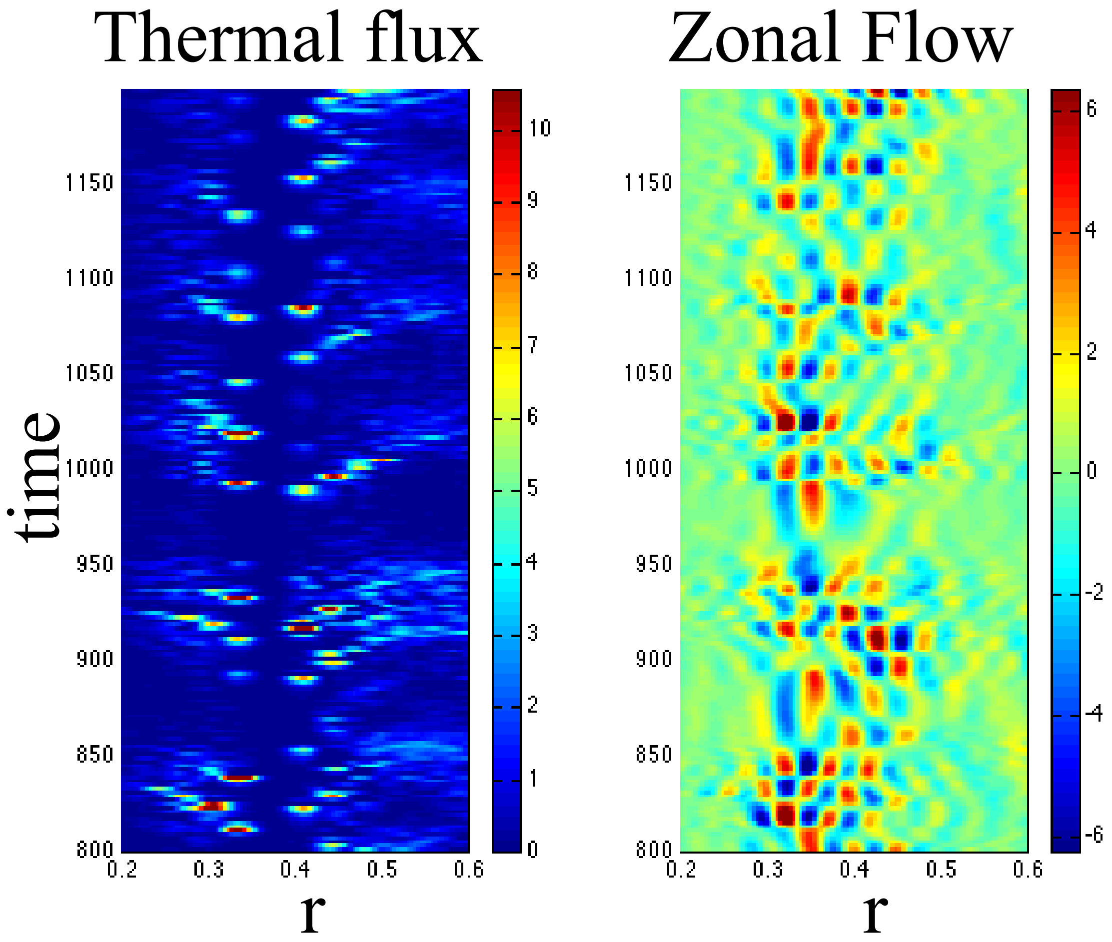
Beyer et al 00

Zonal Flows are active within transport barriers.

- Observed for combined electron and ion barriers.

- Not clear whether ZF participate in the barrier onset.

- Some barriers are quiet.



Conclusions

- Velocity shear is a powerful way of producing a transport barrier.
- There exists other ways to produce a barrier in a tokamak. A barrier is ultimately reinforced by the velocity shear associated to the strong gradient : positive feedback loop.
- Avalanches hardly cross transport barriers. Consistent with suppression due to mean shear flow.
- Zonal Flows are active within some transport barriers. Precise role to be clarified.

Effect of a Shear Flow

- Shear flow rate

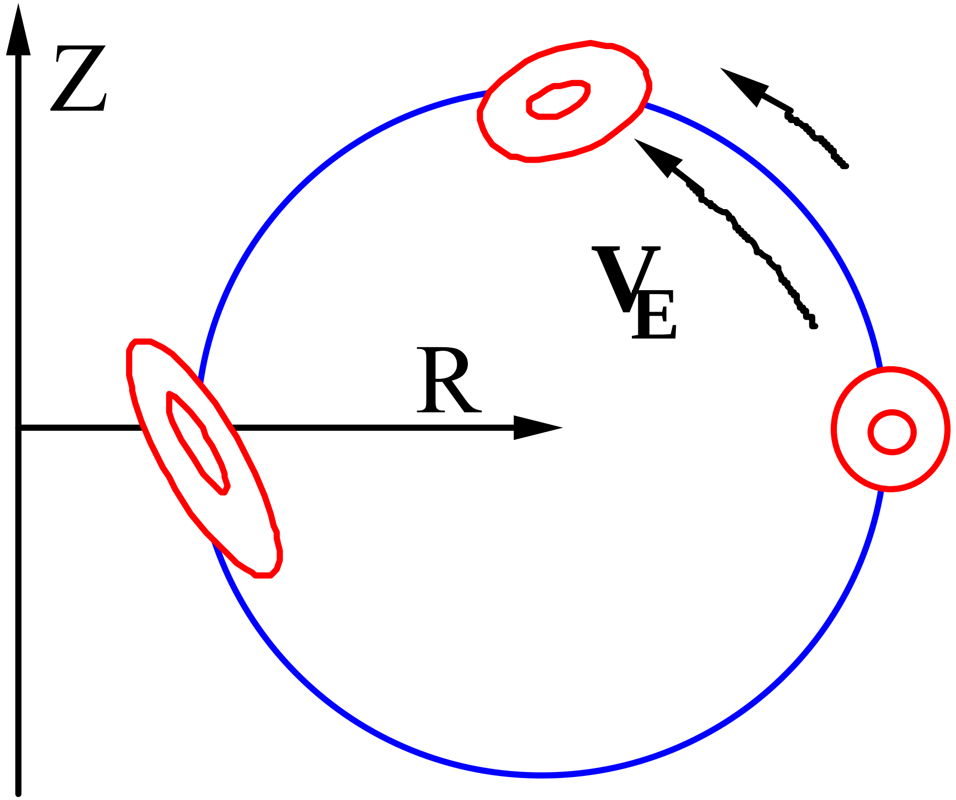
$$V_E' = \frac{dV_E}{dr}$$

- Approximate criterion for stabilisation

$$\left(Dk_\theta^2 V_E'^{\,2}\right)^{1/3} > \tau_c^{-1}$$

Biglari-Terry-Diamond 90

$$V_E' > \gamma\,\text{lin}$$ Waltz 94



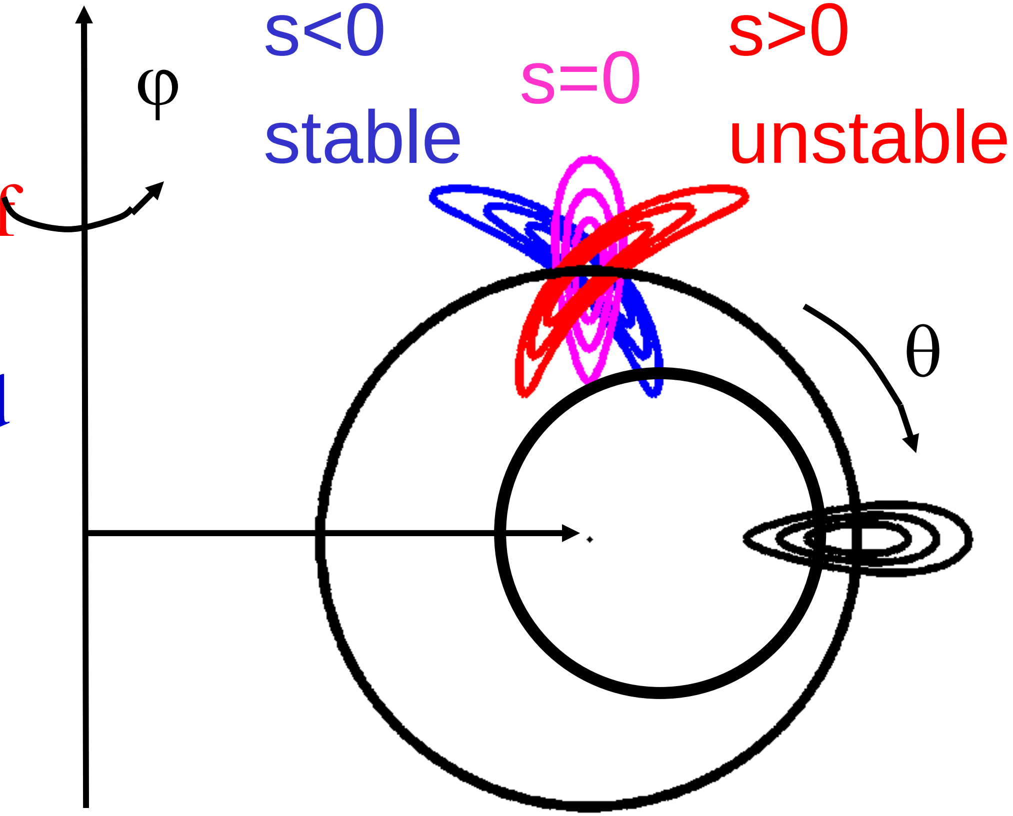
Negative magnetic shear is stabilising

- Magnetic shear :

$$s = \frac{r}{q}\frac{dq}{dr}$$

- s<0 : favourable average of interchange drive $(v_E \cdot \nabla B)(v_E \cdot \nabla p)$ along field lines.
- Enhanced by geometry effect.

B.B.Kadomtsev, J.Connor, M.Beer, J.Drake, R.Waltz, A.Dimits, C.Bourdelle…



Vortex distortion

Strategy for Predicting Turbulent Transport in Fusion Plasmas

- Calculating the plasma response is a challenge: fluid equations (3D, 5 equations at least) or kinetic equations (5D). Simplifications:

- Mean field theory: development of transport models (usually based on a mixing-length approximation)

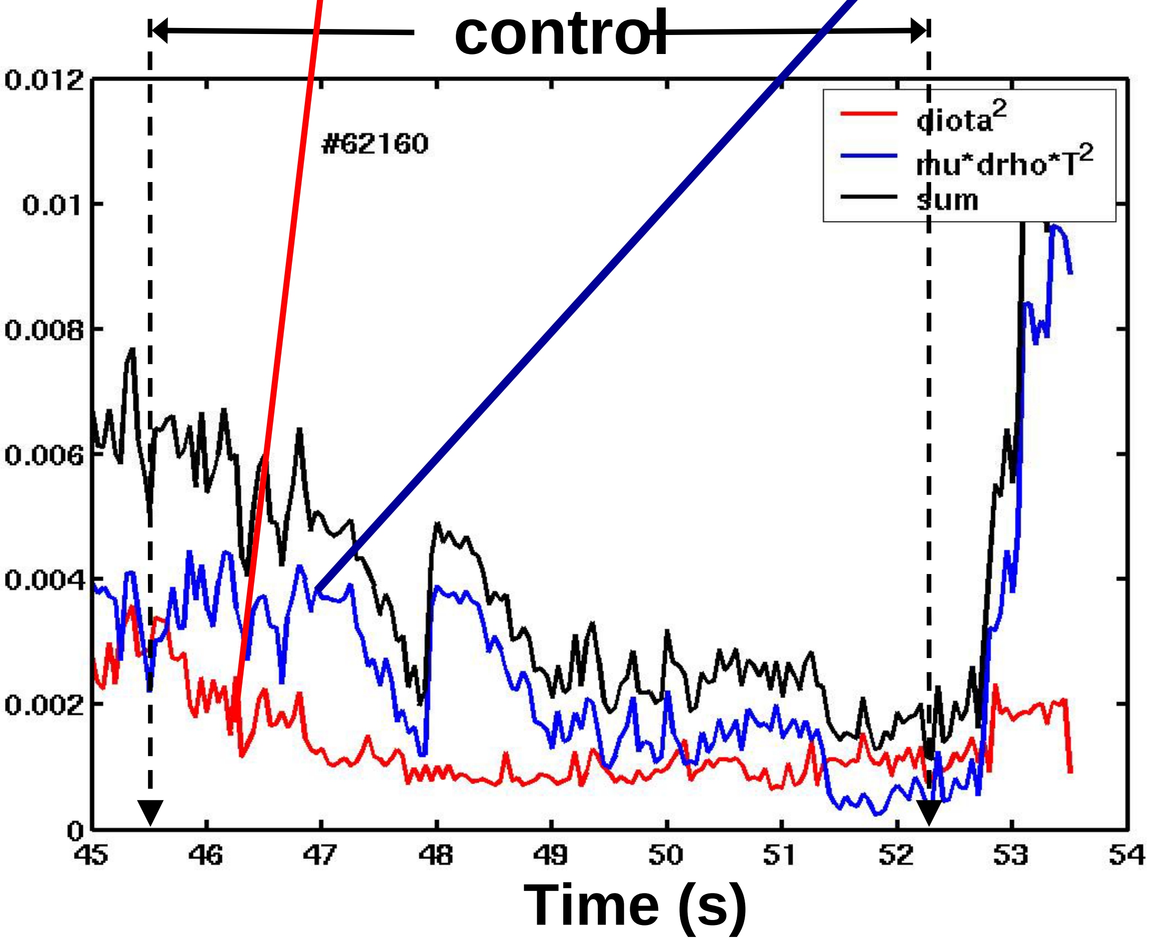
- Statistical theory of turbulent transport.

- Use low resolution turbulence simulations.

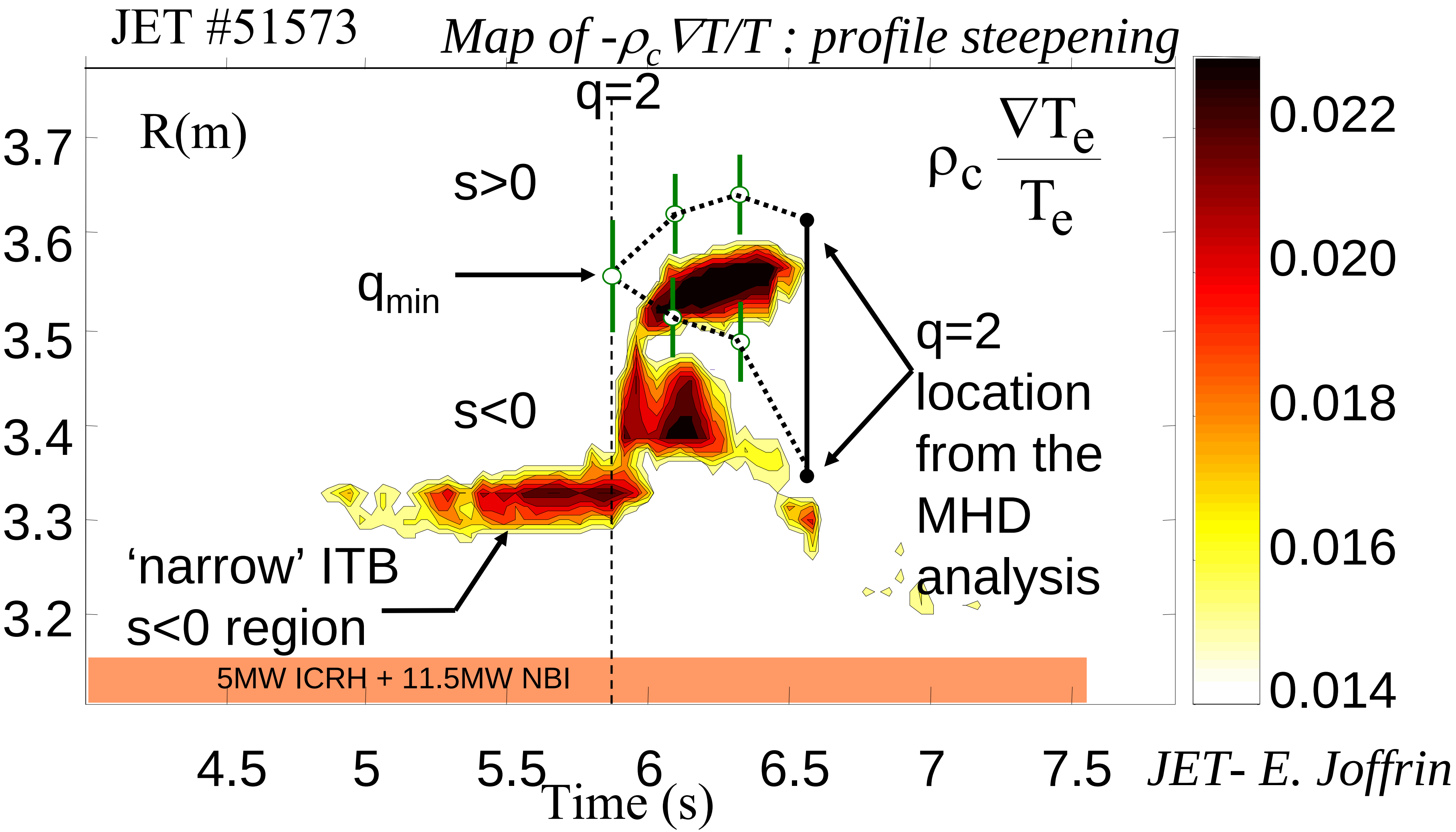
- Develop generic recipes to reduce turbulent transport.

The least square integral error is minimised by the controller

$$\int_0^1 \mu_1(x)\left[q(x)-q_{\text{setpoint}}(x)\right]^2 dx+\int_0^1 \mu_2(x)\left[\rho_{\mathrm{T}}^*(x)-\rho_{\mathrm{T,setpoint}}^*(x)\right]^2 dx$$

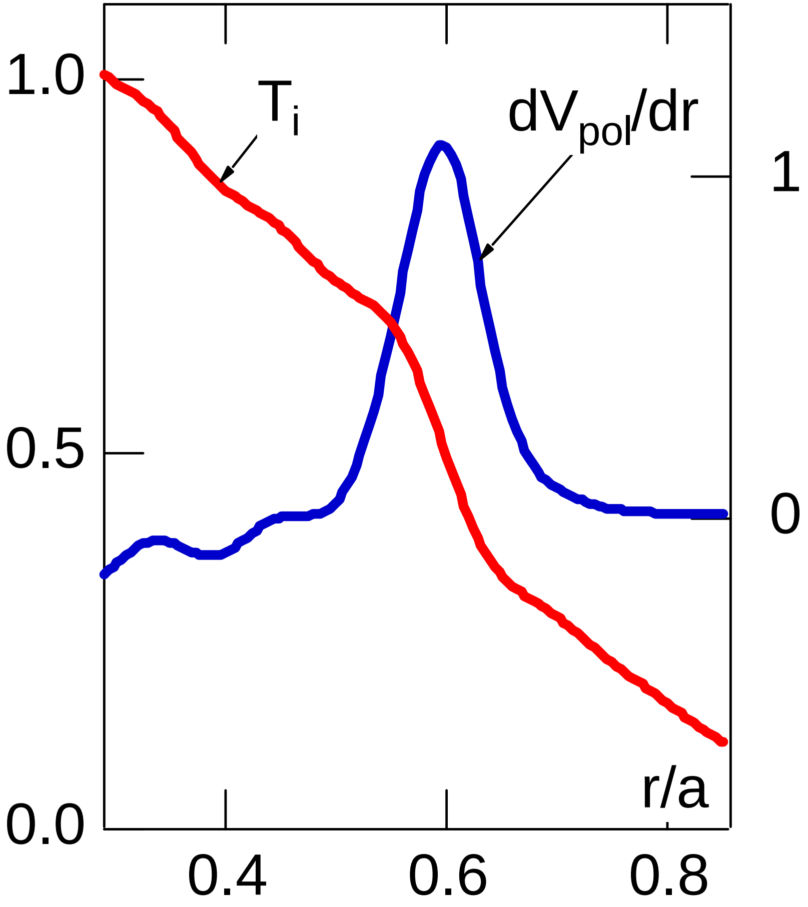


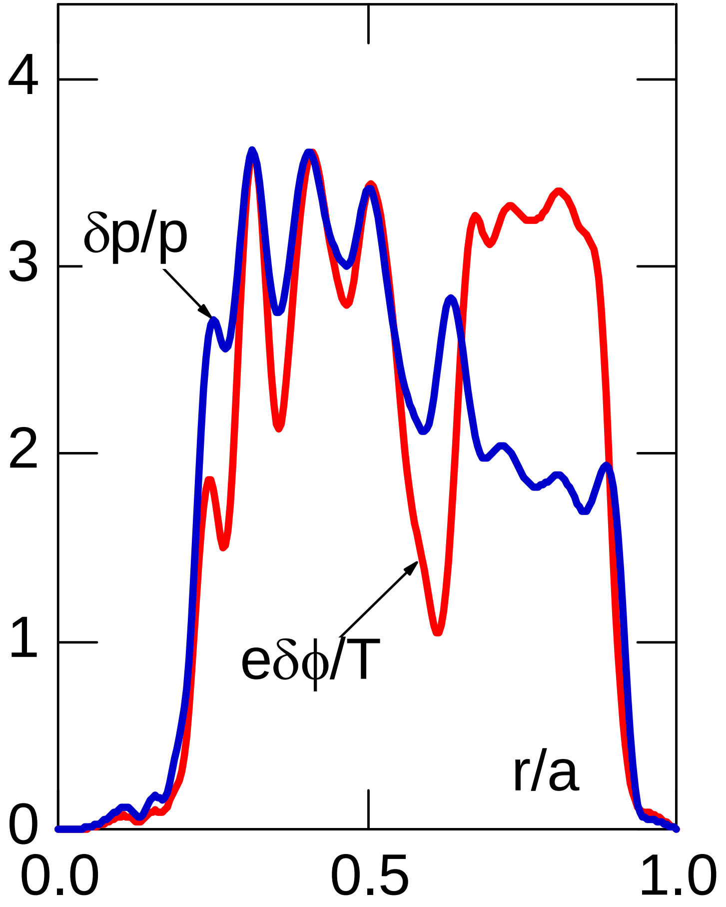
Dynamics of transport barriers is more complex than s<0 and shear flow



JET- E. Joffrin

A shear layer results in a region where the gradients are large: transport barrier





Challenges of profile control

Previous experiments were based on scalar measurements

1. ITB = pressure and current (+ rotation ...) profiles
2. Multiple time-scale system+loop interaction

   Energy confinement time ≠ Resistive time

   Nonlinear **interaction between p(r) and j(r)**

→ Multiple-input multiple-output distributed parameter system (MIMO + DPS)

→ Space-time structure of the system must be determined

Identify a high-order operator model around the target steady state

and try model-based DPS control using SVD techniques

D. Moreau et al., Nucl. Fus. 2003

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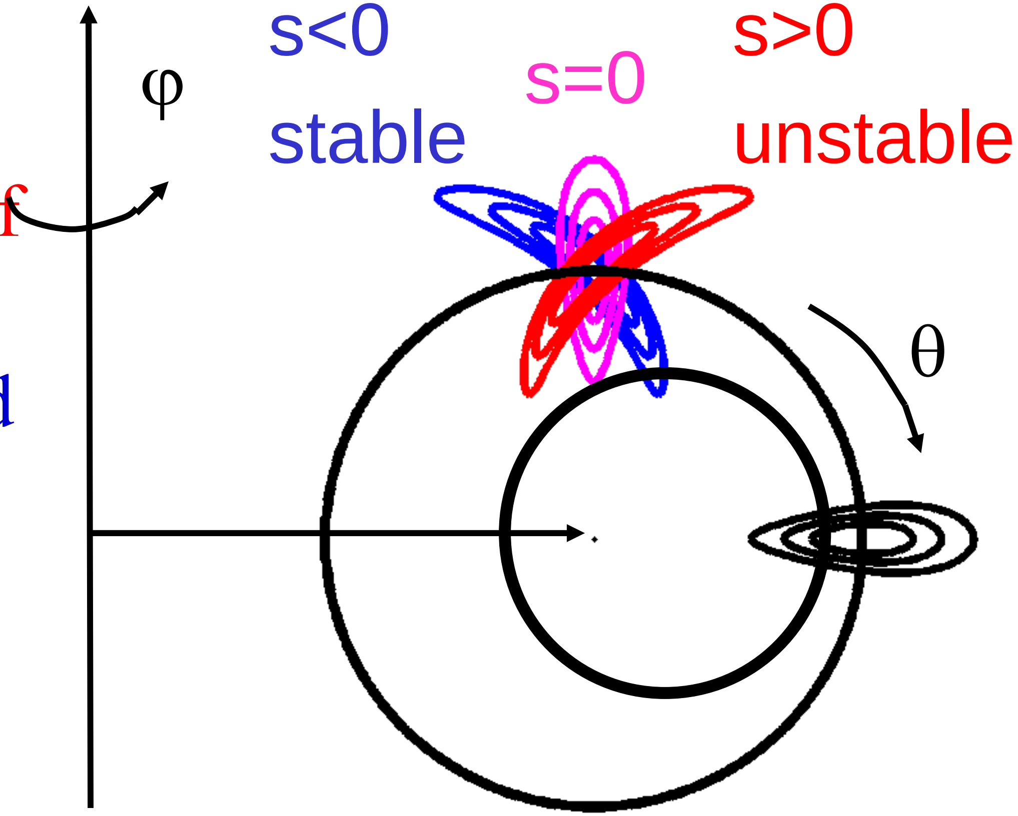

Vortex distortion